

GEOCHEMISTRY OF THE MAFIC MINERALS

IN SOME

YOUNGER GRANITES OF NIGERIA

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ABSTRACT

The plutonic members of the complexes that comprise the Younger Granite Province of Northern Nigeria, include gabbros, syenites, amphibole-fayalite granites and porphyries, amphibole-biotite, biotite, and riebeckite granites, and a short petrographic account of these rocks is given. Mineralogically the plutonic rocks are characterised by a varied assemblage of mafic minerals, of which the most important are members of the olivine, pyroxene, amphibole and biotite groups; all the ferromagnesian minerals are iron-rich.

Analyses have been made of calcium and soda-rich pyroxenes, calciferous and alkali amphiboles, biotites, coesite and ilmenites, that come from some of the above mentioned rocks, and the analytical results are presented and discussed. Whenever possible an attempt has been made to correlate changes in chemical composition of the analysed minerals with variations in optical properties and, in the case of the amphiboles, variations in unit-cell parameters.

Compositional trends in the analysed ferromagnesian minerals have been discussed and compared with compositional trends in the plutonic rocks of the Younger Granite complexes. The possible conditions of formation of some of the analysed ferromagnesian minerals have been considered in the light of experimental studies. The distribution of the complexes throughout the Younger Granite Province is commented upon, and several problems of the evolution of the Younger Granites are discussed.

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INTRODUCTION

The complexes belonging to the Younger Granite Province of Nigeria are scattered throughout an area of approximately 25000 square miles, between latitudes 8° and 12° north, and longitudes 8° and 10° east (see location Map 1).

About forty complexes are known and a large number of these have been mapped in detail. Many of the complexes contain representatives of both volcanic and granitic cycles of activity and, where present, the volcanic rocks are generally older than the granites. Early granite intrusions in the complexes frequently have the form of ring dykes, and these ring dykes may surround central stock or plug-like bodies of later granite intrusions. Basic and intermediate rocks, such as gabbro and syenite, are sometimes associated with the granites but they are always of limited areal extent. The intrusive members of the complexes discordantly cut the Pre-Cambrian basement complex that consists of schists and gneisses, but there has been no contact metamorphism of the basement rocks (Jacobson et. al. 1958).

The precise age of the Younger Granites is unknown, although Holmes and Cahen (1957) on the evidence then available, suggested an early Palaeozoic age. Horne (1955) discussed the results of $^{206}\text{Pb}:\text{U}$ dating of pyrochlore from Kaffo Valley, and proposed an age of 204 ± 40 million years for the mineral. More recent age determinations by Darnley et. al. (1962) have given an age of 159 ± 25 million years to fergusonite, associated with the complexes, from two localities in the Jos area. These authors also consider that the age put forward by Holmes and Cahen should be discounted, as it was based on discordant results given by a monazite, and this view is apparently shared by Cahen (1961).

Previous research:

During the period 1903 to 1911, Falconer recognised that the Younger Granites formed a group of intrusions quite separate from the Older Granites of the Pre-Cambrian basement complex, and since that time a great deal of research has been carried out on the complexes, particularly in relation to the economic mineral deposits associated with them. The results of more recent research have been summarised by Jacobson, MacLeod

and Black (1958) and these authors give details of the distribution and structure of the complexes, as well as a detailed account of the rock types that form the individual intrusions.

Present research:

In 1958 a group from Imperial College, London, led by Dr. J.R. Butler, visited the Jos area and, with the co-operation of the Geological Survey of Nigeria, collected a large number of rock samples from several of the complexes. This material has been used by the staff and research students of the Geochemistry department of Imperial College, for trace element variation studies on the rocks and minerals, and the information that has been obtained has considerably increased the existing knowledge of the chemistry of the granites (Butler et. al. 1962, Bowden, 1961).

The research carried out by the author was a continuation of these previous researches on the Nigerian Granites, and it consisted of a chemical and petrological study of granitic rocks from several complexes. More particularly, the author has investigated the range in chemical composition shown by the members of the pyroxene, biotite and amphibole groups, which are among the more important of the ferromagnesian mineral groups to be found in the Younger Granites.

This thesis presents the results of these investigations and it is divided into three sections:

Section A gives a short account of the petrography of the plutonic rocks from the complexes, including all those rocks from which the author has separated minerals for analysis.

Section B discusses the variations in chemical composition, optical properties, and unit-cell parameters of a number of mafic minerals (cell parameters of the amphiboles were determined by M.T. Frost, B.Sc., of Manchester University).

Section C examines the possible relationships between members of the ferromagnesian mineral groups, as indicated by their compositional trends, and the trends in the minerals are briefly compared with the trends in the granitic rocks from several of the Nigerian complexes. The possible conditions of formation of some of the granites are considered in the

light of experimental work on a number of relevant mineral groups. The distribution of the complexes throughout the Younger Granite Province is dealt with briefly and the nature of the igneous cycle of activity in a number of selected complexes is discussed.

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GEOLOGICAL MAP OF NORTH-CENTRAL NIGERIA SHOWING THE YOUNGER GRANITE COMPLEXES

SECTION A

The plutonic rocks from the Younger Granite complexes:

The plutonic rocks that form the bulk of the complexes include gabbros and syenites, amphibole-fayalite porphyries and granites, amphibole-biotite granites, biotite and albite-biotite granites, arfvedsonite granites and porphyries, and riebeckite and albite-riebeckite granites. The basic and intermediate members of the complexes are relatively unimportant, accounting for only 5% by area of the total of intrusive rocks.

There is no really typical sequence of intrusion of these various rock types in any one cycle of activity, but in a number of granitic cycles the order is (oldest intrusions first):

1. Pyroxene-fayalite or amphibole-fayalite granite or porphyry
2. Amphibole-biotite granite
3. Biotite and albite-biotite granites
4. Riebeckite granite
5. Albite-riebeckite granite

Petrography of the igneous rocks:

Modal analyses of a number of rocks were made by the author, and for this purpose an average of three slides of each rock were used and approximately 5000 counts were made. For porphyritic rocks, separate counts of phenocrysts and groundmass were made if possible, and in such cases up to 12000 counts were made of each porphyry. As far as possible only discrete grains of albite have been included under the heading of modal albite, although there may have been a considerable amount of albite twinning visible in the perthitic feldspar.

All the rocks from which the ferromagnesian minerals have been analysed are described in this section; in addition, in order that the section should be a complete account of the various plutonic rocks occurring in the Younger Granite complexes, descriptions of a gabbro and a number of biotite granites are included although none of the minerals in those rocks has been analysed. The nomenclature used is that given by Jacobson et. al. (1958).

(a) Gabbro:

The Mama Gabbro which comes from the Tof complex (in the southern part of the Sha-Kaleri complex), is a medium to coarse grained biotite gabbro. The biotite in this gabbro is partially altered to chlorite, and the presence of sheaf-like aggregates of biotite or chlorite crystals suggests that there has been limited recrystallisation of some of the biotite. Remnants of the diallage variety of augite are present, but a large proportion of the pyroxene has been converted to uralite. Epidote and calcite are present, the latter apparently being an alteration product of plagioclase feldspar. Iron-titanium oxides are abundant in this gabbro, and they consist of homogeneous grains of magnetite and ilmenite, and occasional magnetite grains which contain exsolution lamellae of ilmenite.

(b) Syenite:

The only syenite studied by the author is PB.48 from Pankshin, the modal analysis of which is given in Table 1. This syenite is of medium grain size and contains a little quartz, abundant orthoclase perthite, in which albite twinning is sometimes visible, and some albite, which is present at feldspar grain boundaries. The original texture of this rock has been partly obliterated and the boundaries between feldspars are often indistinct wavy or sutured lines. Ferromagnesian minerals include interstitial ferrohastingsite, pleochroic from light straw (X) to deep olive-green (Z), associated with iron-oxides or pseudomorphs after fayalite, and a pale-green ferroaugite which has a maximum extinction angle of 45° and which appears to be of early formation.

(c) Amphibole-fayalite porphyries and granites:

Two of the rocks studied are described as porphyries, PB.71 from Shere Hills and PB.13 from Liruei, and their modal analyses are given in Table 1.

In PB.13 phenocrysts of bipyramidal quartz, perthitic alkali feldspar, pyroxene and fayalite, of grain size 1mm to 3mm, lie in a groundmass which contains quartz and feldspar, zircon, calcite, ilmenite and minute feathery crystals of amphibole, and this groundmass is too

<u>TABLE 1</u> Modal analyses Syenite and amphibole-fayalite granites and porphyries						
	PB.48	PB.13*	PB.71	PB.47	PB.94	PB.38
Quartz	1.2	21.8	25.7	27.3	32.6	23.0
Orthoclase and microcline perthite	79.6	62.3	63.6	56.6	60.5	65.1
Albite	11.4	-	1.4	11.9	1.1	3.5
Biotite	-	-	0.3	tr.	2.6	1.4
Hornblende	4.5	6.2	5.1	2.6	2.1	3.5
Fayalite	tr.	3.3	2.8	0.8	0.7	tr.
Opaque oxides	1.0	0.5	0.7	0.2	tr.	0.1
Zircon	0.3	-	tr.	tr.	tr.	tr.
Fluorite	-	-	0.4	0.5	0.4	-
Others (mainly calcite, epidote or allanite	-	tr.	-	tr.	tr.	tr.
Groundmass: Phenocrysts (%)	52:48					

For key to all Tables in thesis, see Appendix 1.

* Phenocrysts only.

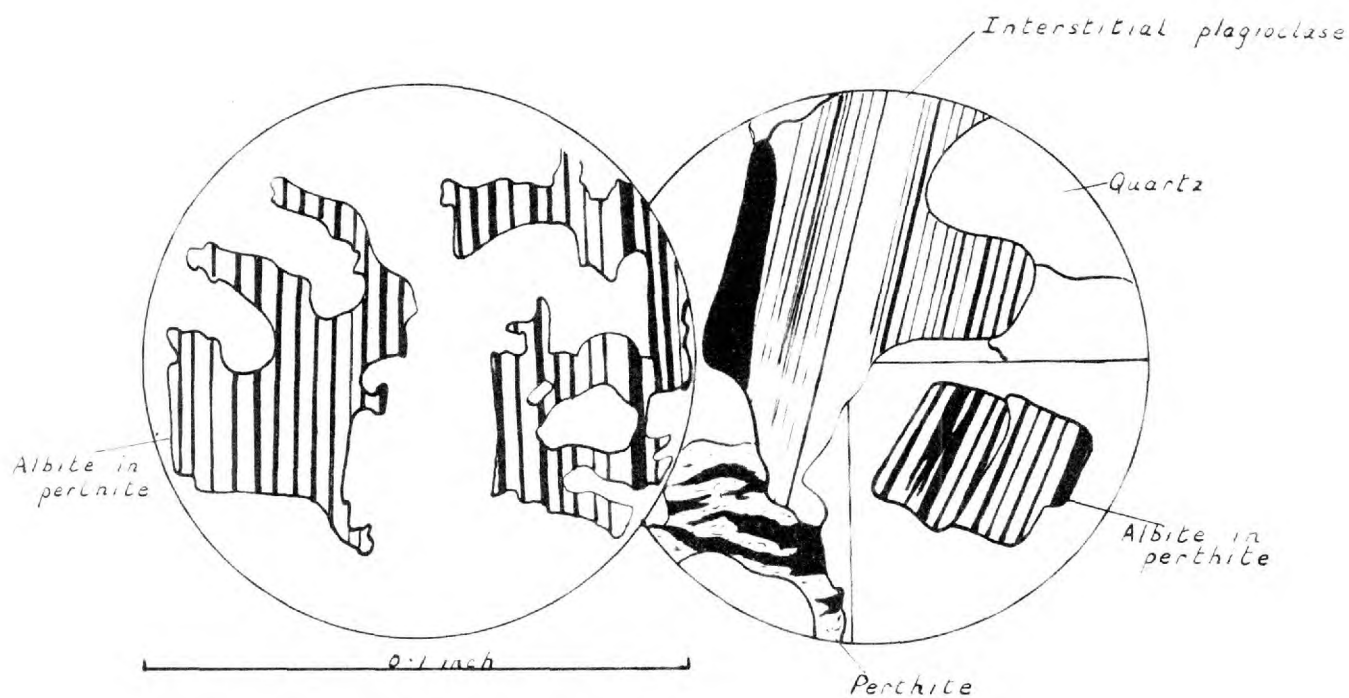
fine-grained for a count to be made of the individual minerals. The quartz crystals are generally well shaped with sharp outlines against the groundmass, but occasionally they are deeply embayed, as are a number of the alkali feldspar phenocrysts. Pyroxene phenocrysts are approximately 1mm in size, they are usually zoned and have what appears to be an altered hedenbergite core that passes out into a green aegirine rim (and this aegirine zone may pass into an outer amphibole rim). No fresh fayalite occurs as phenocrysts but pseudomorphs of possible iddingsite and serpentine after fayalite are present and these are of similar size as the phenocrysts of pyroxene. Some pyroxene, calcite and iron-oxide are associated with these pseudomorphs. Amphibole, of greenish-brown to bluish-green pleochroism, occurs in several forms in this porphyry although never as well shaped phenocrysts. It occurs as reaction rims around the fayalite and pyroxene phenocrysts, the outer edges of this amphibole occasionally having a blue colour and a spongy texture (see Fig. 1). The groundmass contains many completely sieved grains of amphibole that resemble porphyroblasts, and a large number of tiny blue fibroid crystals that apparently crystallised during a very late stage of magmatic cooling.

PB.71 from Shere Hills is a medium textured rock with an average grain size of 1mm and it is generally non-porphyritic, although some coarse perthitic feldspar grains are nearly 5mm in length and a number of fayalite remnants are about 2mm in length. The perthite and quartz show good granitic texture and were apparently formed together. Extreme cloudiness, sutured grain boundaries and very little evidence of unmixing to albite are the main features of the perthitic feldspar. Fayalite is the most important ferromagnesian mineral present and although some of this fayalite is unusually fresh, all stages of serpentinisation and alteration of the mineral can be seen. Very often the altered remnants of fayalite are associated with ilmenite and a very dirty-brown ragged ferrostaurolite which may form a reaction rim to the fayalite. The ferrostaurolite is pleochroic from dull gold to deep greenish-brown and is not very abundant. Minute zircon crystals and small acicular crystals of apatite occur as accessories.

FIG. 1. Some textural features of Nigerian Granites.



(a) Texture of amphibole in PB. 13



(b) Diagrammatic sketches to show difference between nearly discrete grains of albite (left) and discrete grains of albite (lower right), both of which are contained in perthite, and interstitial plagioclase (right)

The amphibole-fayalite granites include PB.47 from Pankshin, PB.94 from Jos-Bukuru and PB.38 from Sha-Kaleri complex, the modal analyses being given in Table 1.

PB.47 has a rather irregular texture due to unmixing of perthitic feldspar and some replacement of quartz and feldspar by albite, but generally the grain size is between 0.5mm and 1.5mm with some coarse interstitial quartz grains and occasional perthites that reach 9mm in length. Straight boundaries between feldspar grains are uncommon, most of the boundaries being wavy, sutured or indistinct. A little of the perthite shows pericline twinning. The amphibole is of grain size 1mm to 1.5mm and is pleochroic from light-brown to deep brownish-green, and although some tabular sections occur which appear to be of early crystallisation, the majority of grains are either ragged and interstitial or ragged and lath-shaped. Fayalite is reasonably fresh in this rock and is present either as small anhedral grains about 0.5mm in size which are being altered to serpentine and iddingsite, or as elongate crystals of 2mm to 3mm length which are only slightly altered. There is a small amount of pale-green pyroxene present, which has a maximum extinction angle near 40° , and which is probably close to ferrohedenbergite in composition. Biotite, iron-oxide, zircon, apatite and some coarse fluorite are accessories.

PB.94 contains ferromagnesian minerals 0.5mm to 1mm in size and quartz and perthite, both of which are between 1mm and 4mm in size, and these two minerals may occur as graphic intergrowths. Albite occurs at the grain boundaries of feldspars and is probably of exsolution origin, but a little of the albite appears to be a late replacement mineral. Biotite is pleochroic from light to dark-brown and is present as small ragged interstitial grains or associated with amphibole, iron-oxide, and fayalite pseudomorphs. Some alteration of the biotite to chlorite has taken place. Stringers of small biotite grains are scattered through the perthite grains and they may be of secondary origin. The amphibole is often subhedral and is present as small grains that are pleochroic from light-brown to deep greenish-brown, but some of it may originally have been in reactions rims around what now appear to be fayalite

pseudomorphs. Abundant iron-oxide, zircon and fluorite are present as accessories.

PB.38 from Kaleri is a generally medium grained rock but the perthitic feldspar grains sometimes reach 6mm in length. Albite twinning is often visible in the perthite which is slightly altered and may show zoning. In patches the feldspar is graphically intergrown with quartz but most of the latter is interstitial. Amphibole grains are rarely more than 1mm in length and although there are some tabular sections, many of the grains are ragged and interstitial to quartz and feldspar. Slight zoning can be seen in a number of the amphibole grains and the mineral is strongly pleochroic from light-straw to deep brownish-green. Very rare small grains of bluish-green amphibole also occur. Biotite, which is pleochroic from light-straw to brownish-black, is present mainly in grains less than 1mm in length and many sections are tabular in shape. One or two patches of a green secondary mineral may be serpentine after fayalite and accessory minerals include zircon, iron-oxide and apatite.

(d) Amphibole-biotite granites:

Several of these granites have been studied, including PB.36 from Kaleri, PB.87 from Amo, PB.45 and PB.51 from Pankshin, PB.24 from Sara-Pier and PB.96 and PB.97 from Jos-Bukuru. Modal analyses are given in Table 2.

PB.36 has a good granitic texture and an average grain size between 1mm and 3mm. Patches of the perthite are strongly sericitised and there is very little exsolved albite visible. The original ferromagnesian minerals, biotite and amphibole, are also altered, particularly the biotite which is green in colour. Opaque iron-oxide is a common associate of these altered minerals.

PB.87 is a medium to coarse grained rock in which the minerals are between 1.5mm and 5mm or more in size. Microcline perthite and quartz are abundant, compared with albite and the ferromagnesian minerals which are of sparse occurrence. Boundaries between feldspars are often indistinct and sometimes replaced by a narrow zone of intergrown tongue-like protrusions of feldspathic material. Less commonly a line of tiny albite crystals

TABLE 2

Modal analyses
Amphibole-biotite granites

	PB.36	PB.87	PB.45	PB.51	PB.24	PB.96	PB.97
Quartz	42.0	31.3	27.8	33.5	26.6	18.5	27.8
Orthoclase and microcline perthite	55.4	66.8	49.8	57.7	69.7	68.7	66.1
Albite	tr.	tr.	16.2	2.0	1.7	3.6	2.8
Biotite)			3.3	2.0	tr.	3.3	1.6
Hornblende)	1.7	1.2	2.4	3.1	1.2	4.7	1.9
Fayalite	-	-	-	-	-	tr.	-
Opaque oxides	tr.	(	0.2	1.4	0.3	0.5	0.1
Zircon	-	(0.4	tr.	-	(	tr.	tr.
Fluorite	tr.	(	tr.	-	(0.3	0.5	-
Others (mainly calcite apatite and allanite)	-	tr.	tr.	-	-	-	-

delineates the microcline feldspar grain boundaries. Biotite occurs in patches and although a little of it is interstitial the majority appears to have formed contemporaneously with quartz and perthite. In colour the biotite is pleochroic from gold to brownish-black. Rare grains of greenish-brown amphibole occur interstitially.

In PB.45 the perthite grains are between 1mm and 5mm in length and may contain albite crystals which appear to have been exsolved. Other subhedral grains of albite which occur in the rock are of uncertain origin although a few appear to be replacing perthite. Quartz is granular or interstitial and up to 4mm in diameter. Subhedral amphibole is present, 1mm to 2mm in length, and it is strongly pleochroic from light-buff to deep blackish-green and many of these amphibole grains have a biotite core. Most of the biotite is subhedral and apparently formed with the amphibole; well shaped grains of both amphibole and biotite occur together and may be surrounded by more ragged patches of the same minerals. Slight alteration of the amphibole and biotite has taken place. Small zircon crystals, a little iron-oxide, strongly zoned allanite, acicular apatite crystals and some fluorite, are the accessories.

PB.51 is also from Pankshin and contains similar accessory minerals to PB.45. The perthite grains, which are less than 1mm to approximately 4mm in size, contain only a little exsolved albite and many of the exsolution lamellae of albite are highly curved. Quartz has an average size of 1mm but grains up to 4mm in size are present. The amphibole, which is pleochroic from light-straw to brown, is sometimes patchily zoned, commonly twinned, and the grains are often ragged and usually 1mm or less in length. Biotite rarely occurs as well shaped grains and may be interstitial to the felsic minerals.

PB.96 and PB.97 are early hornblende-biotite granites from Vom and Jos-Bukuru complexes; both rocks are coarse textured and the perthitic feldspar may be intergrown with quartz. Patches of nearly discrete albite grains (Fig. 1) showing sharp lamellar twinning occur in a number of the perthite grains and albite also appears at feldspar grain boundaries. Pericline twinning is also well developed in the plagioclase of PB.97. The biotite is strongly pleochroic from dark-brown to nearly colourless;

it is commonly interstitial or it may occur as trains of ragged grains, less than 1mm long occurring in the felspar. The amphibole is pleochroic in light-browns and deep-greens and forms elongate interstitial grains up to 1.5mm long, or it occurs with biotite in clusters of mafic minerals which include biotite, amphibole in tuft-like aggregates, and iron-oxides, and these minerals are associated with patches of very spongy amphibole and sheaves of small biotites. Accessories are fluorite, coarse zircons, and acicular grains of apatite.

PB.24 from Sara-Fier contains coarse perthite grains up to 8mm in length together with smaller perthite grains between 0.5mm and 2mm in size. Albite is visible in some of the perthite but is rarely developed at grain boundaries. Many of the smaller perthite grains have extremely sutured, indistinct grain boundaries and some recrystallisation may have occurred in these areas. Quartz is less coarse than the perthite, forming grains up to 3mm in size, and it is often fractured. A brownish-green amphibole is the most abundant ferromagnesian mineral present and some grains of this amphibole have a bluish-green margin. The rock also contains patches of a bluish-green fibrous amphibole, ilmenite, a little dark-coloured biotite, epidote, coarse zircon crystals and small grains of fluorite.

(e) Biotite granites:

Two biotite granites from Amo complex, the Rough Range biotite granite and the Amo Peak biotite granite, contain microcline perthite. In the former granite, replacement and exsolution albite occurs, and there is also a small amount of greenish-brown amphibole present. The biotite in the Amo Peak biotite granite is slightly altered.

Two albite-biotite granites, the Rayfield-Gona albite-biotite granite from Jos-Bukuru and the albite-biotite granite from the north Sara Hills, contain abundant albite, and there appears to have been some recrystallisation of felspar in the Rayfield-Gona granite.

(f) Arfvedsonite granite and porphyry:

Only two of the rocks (relating to this thesis) have been described as arfvedsonite bearing, and these are the Hotum arfvedsonite Granite from Sha-Kaleri (PB.37), and PB. 6 from Liruei which is a porphyry.

The modal analyses of these two rocks are given in Table 3.

PB.37 is a medium grained rock rich in ferromagnesian minerals and also perthitic feldspar, which contains little albite and which is frequently intergrown with quartz. The arfvedsonite is strongly pleochroic in light-browns and bluish-greens, but the colour is variable and the mineral is usually intensely zoned. Some of the arfvedsonite occurs interstitially or as small grains which merge into fibrous aggregates, but a high percentage of the mineral occurs, often as partly rounded grains, in clusters of mafic minerals which include serpentine and iddingsite pseudomorphs after fayalite, iron-oxide and remains of aegirine or aegirine-rimmed pyroxene. A considerable number of small euhedral or subhedral grains of aegirine and fayalite pseudomorphs occur enclosed in the perthite grains, together with small grains of iron-oxide and fluorite. An interesting feature of the rock is the number of xenoliths of earlier, often porphyritic, granite that it contains.

PB. 6 has phenocrysts of perthite, quartz, pyroxene, amphibole and fayalite pseudomorphs, of grain size between 0.5mm and 3mm, set in a groundmass of similar minerals and of grain size 0.05mm to 0.5mm. The perthite is sometimes twinned on the Raveno law and does not show extensive unmixing features. Some overgrowth of feldspathic material on the perthitic feldspar appears to have taken place as the original outlines of the perthite can often be seen within the new grain boundaries which are indistinct and embayed. A similar embayment is also seen at the margins of many of the quartz phenocrysts. Only a few pyroxene phenocrysts occur and these may be zoned (particularly in the finer-grained facies of the rock), the outermost zone being pleochroic from emerald green to deep emerald green. These pyroxene phenocrysts may also be partly mantled by amphibole but generally the amphibole occurs as phenocrysts which are pleochroic from greenish-brown to bluish-green, and as reaction rims to the fayalite. In the groundmass the amphibole forms ragged interstitial grains of late formation. Calcite, fluorite and rare grains of deep-red biotite also occur in the groundmass.

(g) Riebeckite granites:

The riebeckite granites have been described as riebeckite-

TABLE 3

Modal analyses
Arfvedsonite porphyry and granite

	PB. 6		PB.37
	Groundmass	Phenocrysts	
Quartz	37.1	20.4	20.1
Orthoclase and microcline perthite	53.6	77.2	67.2
Albite	-	-	1.9
Amphibole	5.1	1.2	7.9
Aegirine	-	-	tr.
Pyroxene	2.9	1.7	tr.
Fayalite	1.0	0.5	2.4
Opaque oxides	tr.	0.3	0.2
Zircon	tr.	-	0.3
Others (fluorite, calcite, allanite and chlorite)	tr.	tr.	tr.
Groundmass: Phenocrysts	54:46		

biotite, riebeckite, aegirine-riebeckite, or albite-riebeckite granites, but it should be emphasised that the number, and kind, of ferromagnesian minerals to be found in an intrusion of any one of these rock types, appears to vary slightly in different parts of the particular intrusion. The modal analyses of these granites are given in Table 5.

PB.29 comes from the biotite-rich facies of the riebeckite-biotite granite found in the Amo Complex, the outer margin of this intrusion being almost free of biotite although riebeckite and astrophyllite are abundant. Biotite increases relative to riebeckite on going toward the inner margin of the intrusion, and in the inner margin the two minerals are present in approximately equal proportions. PB.29 is from this inner margin and PB.30, which is described later, comes from the riebeckite-rich outer margin.

PB.29 is a medium textured rock of grain size 1mm to 3mm, but occasionally the perthite grains reach 6mm in length. The perthite is a microcline variety in which the grain boundaries are often blurred or indistinct or marked by very small albite crystals. Albite twinning is commonly seen in the perthite. Most of the quartz appears to have crystallised with the felspar but a little of it is obviously interstitial to the other minerals and is of late formation. The biotite has a very striking appearance, being pleochroic from a bright foxy-red to a deep dull-brown, and it usually occurs in clusters of grains which are up to 1mm in length. The riebeckite is also present in grains up to 1mm in length and is pleochroic from light olive-green to blue-black.

Although the texture, amount of albite present, and distribution of dark minerals varies considerably, from section to section and from rock to rock, the most important features of the other riebeckite granites can be summarised:

A small number of the riebeckite granites, PB.50, PB.57 and PB.58 from Sara-Fier, are medium to coarse grained rocks containing abundant vein perthite which shows very little evidence of exsolution of albite or of replacement by the latter. Riebeckite is sparsely developed and may be found interstitially or as feathery aggregates of very small crystals of late formation, and the mineral may be zoned or twinned. No

TABLE 5

Modal analyses of riebeckite granites

	R. 3	R. 7	R.20	R.50	R.57	R.58	R.63	R.64	R.65	R.83	R.84	R.85	R.30	R.79	R.92
Quartz	29.9	27.0	34.9	36.4	33.6	31.2	34.7	32.8	32.3	32.6	28.1	36.4	23.7	32.1	28.0
Alkali feldspar (perthitic)	42.7	58.2	62.1	60.1	64.9	62.7	49.9	52.9	56.2	55.9	58.1	53.3	66.2	48.8	59.6
Albite	13.3	9.1	1.2	2.6	tr.	0.8	7.4	8.7	7.4	7.4	5.7	7.8	4.4	12.3	5.2
Biotite	-	0.3	-	-	-	-	-	tr.	-	-	-	-	-	-	-
Amphibole	8.1	2.4	1.8	0.5	1.3	4.6	5.3	4.0	)1.6	2.1	5.8	0.4	6.7	3.8	4.2
Aegirine	1.0	2.9	-	-	-	-	2.2	1.3		0.7	1.5	-	-	-	2.8
Opaque minerals	-	-	tr.	-	-	tr.	-	-	-	0.7	0.2	1.4	-	-	-
Zircon	-	0.3	tr.	-	tr.	tr.	-	-	-	-	-	-	tr.	-	tr.
Pyrochlore	1.2	-	-	-	-	-	-	-	-	-	-	-	-	0.3	-
Cryolite	3.1	-	-	-	-	-	-	-	-	-	-	-	-	2.5	-
Topaz	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	-
Astrophyllite	-	-	-	0.4	tr.	-	-	-	-	0.5	0.3	0.3	tr.	-	-
Calcite	-	-	-	-	-	-	-	-	-	-	0.1	0.4	-	-	-

aegirine is present. In PB.30 from Amo the riebeckite may occur as small late interstitial grains or as elongate ragged grains, but there is a great deal of replacement albite present and the texture is less uniform than that of the previous group of riebeckite granites.

Several of the rocks, PB. 7 and PB.20 from Liruei, PB.63, PB.64 and PB.65 from Shere Hills, PB.83 and PB.84 from Kigom Hills and PB.92 from Buji, contain both aegirine and riebeckite. These rocks vary considerably in grain size and texture and in the degree of exsolution and albite replacement that they show. The relative proportions of riebeckite and aegirine are also variable; in PB.20 they are approximately 1:1; in PB.65 there is very little aegirine, and in the others the ratio of riebeckite:aegirine is 2 or 3:1. Both minerals may be of early or late formation, either may act as core to the other (even in the same rock section), they may form parallel elongate intergrowths, and occasionally they replace one another. In PB.63 large riebeckite crystals are often partly mantled by very small late formed aegirine crystals, and small aegirine grains have also formed along fractures in some of the riebeckite grains. Zoning may occur in both minerals and the riebeckite does not always go into extinction.

PB. 3 from Liruei and PB.79 from Amo show very extensive replacement of all other minerals, including riebeckite, by small albite laths. These two rocks also have a number of uncommon accessory minerals, including cryolite (distinguished from fluorite by its pseudo-isotropic character), pyrochlore, and topaz. The felspar in PB.79 is dominantly microcline-perthite.

Common accessories in many of these granites include astrophyllite, fluorite, allanite, biotite, and zircon. PB.83 and PB.84 from Kigom Hills also contain ore minerals (molybdenite, pyrite and chalcopyrite) which are accompanied by calcite.

Summary of the main petrographic features of the granites:

Amphibole granites: The amphibole in these rocks frequently forms a reaction rim to the fayalite or pyroxene. Fresh fayalite is uncommon and the mineral is either altered or it is present as remnants. In the porphyries the phenocrysts are euhedral or subhedral and quartz may be

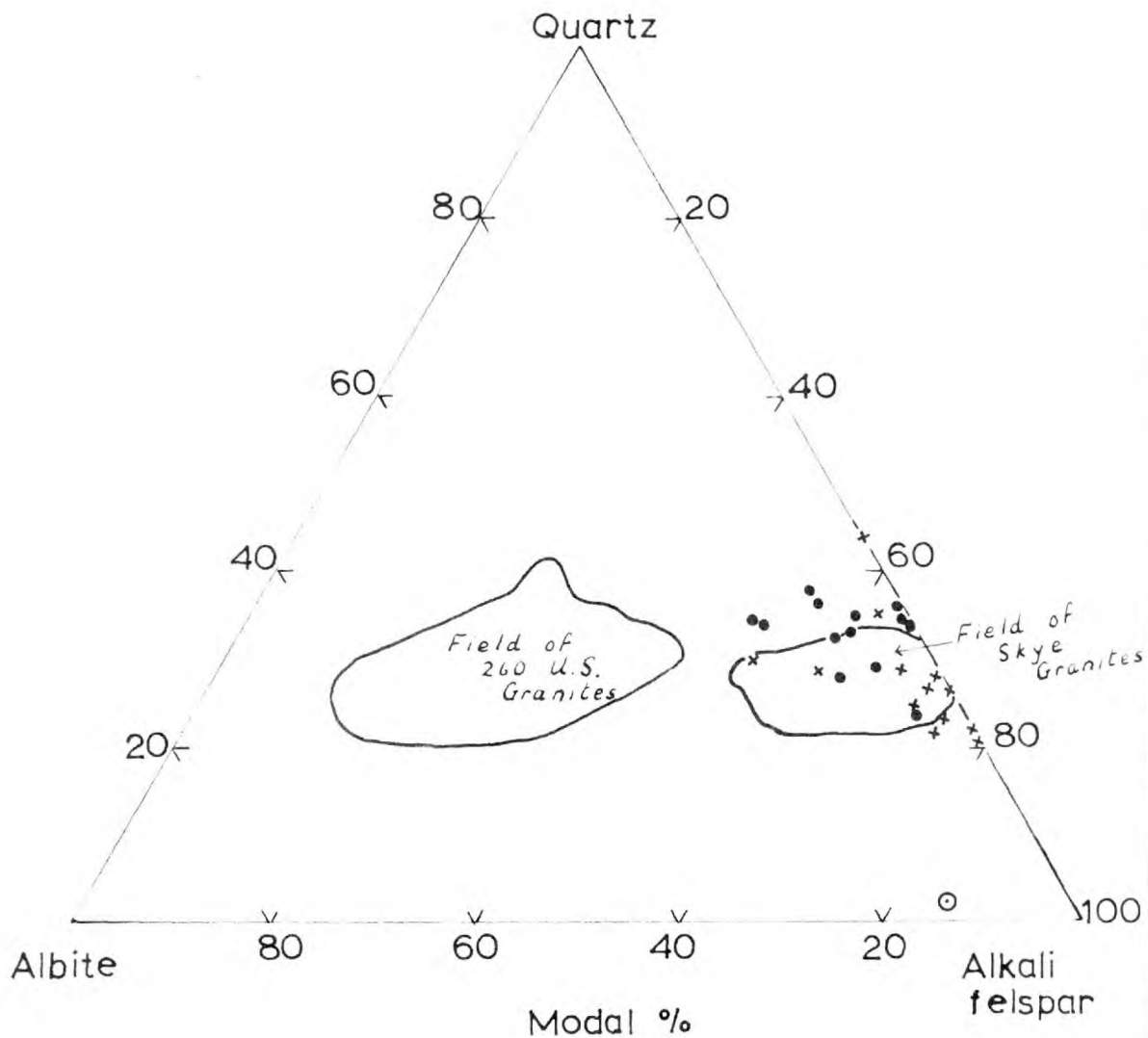
present as the high temperature bipyramidal form. Perthitic alkali feldspar is always abundant but the percentage of modal albite is variable.

Amphibole-biotite granites: In these granites the textures are of medium to coarse type. Ferromagnesian minerals may have a subhedral form but they are often interstitial to quartz and feldspar and of late formation. The biotite in the granites is often altered.

Biotite and riebeckite granites: Exsolution and replacement textures in the perthitic feldspar are common in these rocks and the proportion of replacement albite is high in the albite-biotite and albite-riebeckite granites. Aegirine is a frequent associate of the alkali amphibole in the riebeckite granites.

In Fig. 2 the modal compositions of the granites previously discussed have been represented in terms of the three main components: quartz, alkali feldspar and albite. The Nigerian granites show some similarity in their modal compositions to the Skye granites (Bowen and Tuttle, 1947) but they occupy a slightly more extensive field than the latter granites. However, the author has previously pointed out that where possible only discrete grains have been included under the heading of modal albite; if all the patchy areas of albite in the perthitic alkali feldspar had been included in the modal albite, it would have shifted the field occupied by the Nigerian granites further toward the albite apex in Fig. 2.

FIG: 2 Modal composition of Nigerian Granites compared with granites from the United States and Skye. (Tuttle and Bowen, 1958).



- Nigerian
- ° Riebeckite granites
 - + Amphibole-biotite granites
 - ⊙ Pankshin syenite

SECTION B.

MAFIC MINERALOGY OF THE YOUNGER GRANITES

MAJOR SILICATE GROUPS:

(1) Pyroxene group:

Pyroxenes occur in many of the igneous rocks from the Younger Granites and in composition they can be divided into (a) calcium-rich and (b) soda-rich pyroxenes.

(a) Calcium-rich pyroxenes:

Pyroxenes of this type occur as a major constituent of the basic and intermediate rocks and amphibole-fayalite-pyroxene granites and porphyries but, unfortunately, it is always difficult and very often impossible to separate sufficient fresh material for analysis.

Table 5a gives the analysis, formula and optical properties of Px.48, a ferroaugite from the Pankshin syenite (PB.48). The formula has been calculated on the basis of six oxygen atoms in accordance with the method proposed by Hess (1949). Analyses of a number of other ferroaugites from Icelandic pitchstones, discussed by Carmichael (1962), have been reproduced in Table 5b for comparative purposes.

Attempts to determine the composition of other calcium-rich pyroxenes from the Younger Granites by means of optical data were abandoned, as the composition of the analysed specimen could not be accurately deduced from the optical curves of either Muir (1957) or Carmichael (1960), and because pyroxenes from the Nigerian granites often show marginal alteration that affects refractive index measurements.

Compared with the ferroaugites from the Icelandic pitchstones, Px.48 contains slightly less Si and more Al in the Z-group, and in these respects it is more comparable with several of the ferroaugites from the Skaergaard intrusion. It also contains more Ti, Al, Fe⁺⁺⁺, and alkalis (particularly K) in the WXY-group than does the average Icelandic ferroaugite. The relatively large amount of Al and Fe⁺⁺⁺ in octahedral co-ordination might be responsible for the high value of β for this pyroxene. Fig. 3 shows the position of the Nigerian ferroaugite in relation to the trends of the Icelandic and Skaergaard pyroxenes.

(b) Soda-rich pyroxenes:

Pyroxenes which are very close in composition to end-member

TABLE 5(a)

Chemical analyses of pyroxenes, and formulae calculated to 6 oxygen atoms

	Ag.20	Ag.92	Ag. 3	Px.48
SiO ₂	50.05	50.66	51.92	47.82
ZrO ₂	0.16	0.15	n.d.	n.d.
Al ₂ O ₃	0.45	0.59	1.85	2.59
TiO ₂	1.58	0.65	0.77	0.75
Fe ₂ O ₃	29.95	33.27	31.44	3.37
FeO	2.89	0.82	0.75	20.55
MnO	0.33	0.08	-	0.89
MgO	tr.	0.05	-	4.76
CaO	1.91	0.29	-	18.52
Na ₂ O	12.59	13.65	12.86	0.90
K ₂ O	0.28	0.23	0.19	0.26
H ₂ O ⁺	n.d.	n.d.	0.17	n.d.
-	0.06	0.03	n.d.	n.d.
	100.25	100.47	99.95	100.41
Atomic %:				β 1.733-5
Ca				41.8
Mg				15.0
Fe ⁺⁺				43.2
<u>Z</u> { Si	1.941	1.957	1.98	1.894
{ Al	0.021	0.027	-	0.091
{ Zr	0.003	0.003		
{ Ti	0.035	0.013		
{ Ti	0.011	0.006	0.02	0.022
{ Al	-	-	0.08	0.030
{ Fe ⁺⁺⁺	0.874	0.968	0.90	0.100
{ Fe ⁺⁺	0.094	0.026	0.02	0.681
<u>WXY</u> { Mn	0.011	0.003	-	0.030
{ Mg	-	0.003	-	0.281
{ Ca	0.079	0.012	-	0.786
{ Na	0.946	1.023	0.95	0.069
{ K	0.014	0.011	0.01	0.013
<u>Z</u>	2.000	2.000	1.98	1.985
<u>WXY</u>	2.029	2.052	1.98	2.012

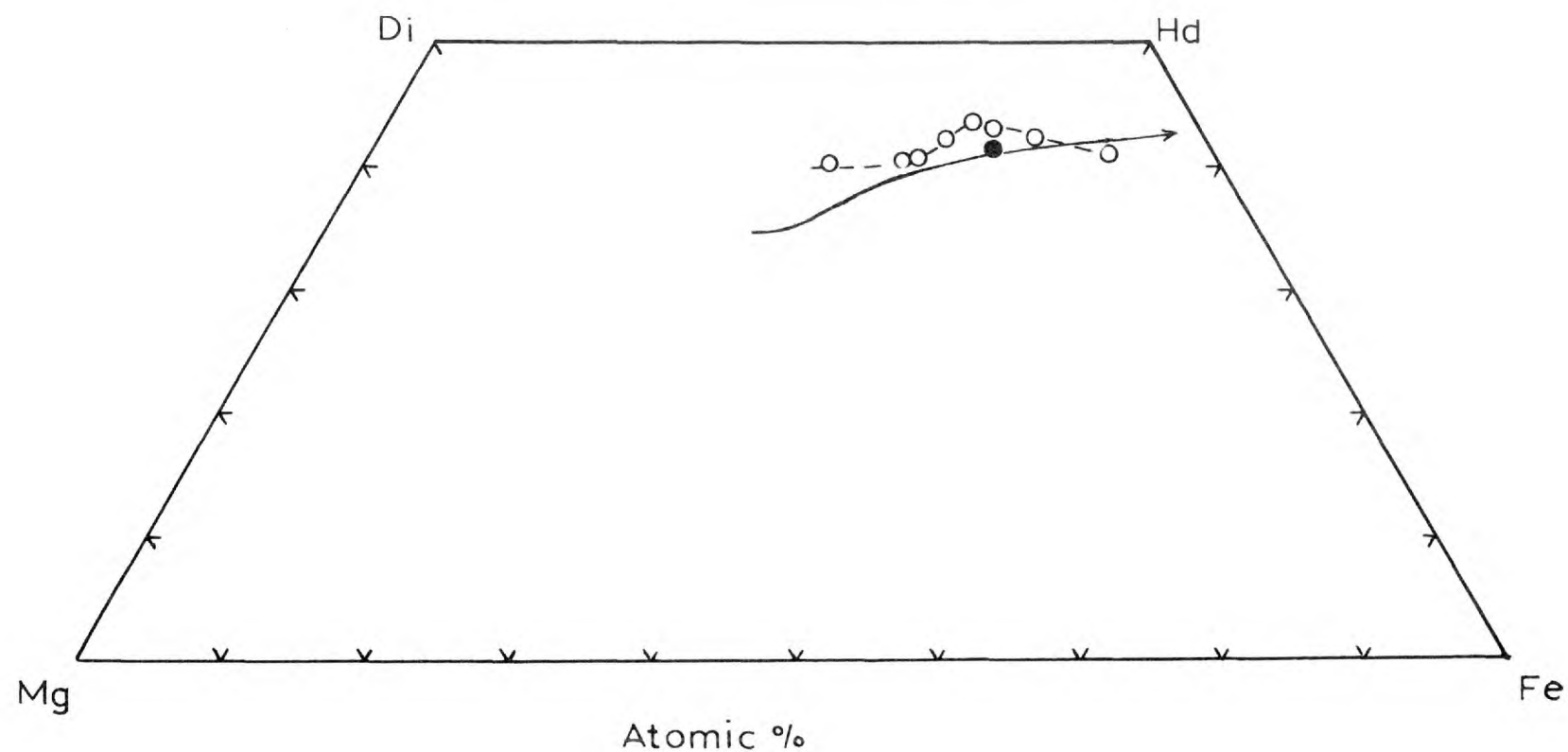
TABLE 5(b)

Chemical analyses of ferroaugite from Icelandic pitchstones

	1.	2.	3.	4.
SiO ₂	48.76	48.01	49.05	49.10
Al ₂ O ₃	0.99	2.42	1.61	1.07
TiO ₂	0.47	0.91	0.48	0.63
Fe ₂ O ₃	3.36	2.21	1.85	3.17
FeO	19.42	20.32	21.40	21.97
MnO	0.73	1.23	0.98	0.98
MgO	5.93	5.07	4.52	3.70
CaO	19.47	19.92	19.32	18.86
Na ₂ O	0.66	0.39	0.57	0.92
K ₂ O	0.11	0.04	0.14	0.11
	99.90	100.52	99.92	100.51
<i>B</i>	1.726	1.727	1.726	1.732
Atomic %:				
Ca	42.5	43.9	43.4	42.6
Mg	18.0	15.6	14.1	11.7
Fe ^{II}	39.5	40.5	42.5	45.7

FIG. 3

Position of Nigerian Ferroaugite
in relation to trends in
Icelandic and Skaergaard
ferroaugites.



o-o Icelandic pyroxene trend,
Carmichael (1960)

● Nigerian ferroaugite (analysed)

→ Skaergaard ferroaugite
trend. (Brown, 1960)

aegirine ($\text{NaFe}^{+++}\text{Si}_2\text{O}_6$) are of sporadic occurrence in the riebeckite granites but, with a few exceptions, they are always modally insignificant.

Table 5a gives the analyses and formulae of three aegirines from riebeckite granites, two of which were analysed by the author and the other by F.A. Gonyer (discussed by Greenwood, 1951).

The most interesting features of the analyses of these aegirines are the extremely high contents of soda and ferric iron. Atomic proportions of alkali are always slightly in excess of ferric iron and this appears to be common in acmitic pyroxenes (see Sabine, 1950). Ag.20 has a surprisingly high content of ferrous iron, but the amount was confirmed by a duplicate analysis. The CaO content of this aegirine is also high and compares with that (1.80%) of an aegirine occurring in a syenite from the Morotu District of Sakhalin, reported by Yagi (1953). Both Ag. 20 and Ag.92 are deficient in Si and Al compared with the aegirine from Kigom, and a small amount of Ti had to be included in the Z-group of these two minerals.

The most unusual of the three aegirines is Ag.92, the soda content of which is 13.65%, compared with a theoretical limit for aegirine of 13.41%. To check the accuracy of the soda determination a triplicate analysis was carried out, on different amounts of sample and on separate occasions. Two of the determinations were made by the author and the other by Dr. I.S.E. Carmichael; the results confirmed the very high soda content of Ag.92. Possible explanations for this excess soda content are (a) the mineral crystallised from a residual magmatic liquid that was enriched in soda and was slightly deficient in total iron and (b) there has been some deuteric replacement of ferric iron by alkali in this mineral. No convincing evidence can be given to support (a) as the aegirine in the rock concerned (PB.92) appears to have formed with the alkali amphibole R.92 which, although very rich in soda, is not abnormally enriched in the latter component relative to iron. Somewhat better evidence can be advanced in support of (b); albite has replaced some of the original feldspar of the rock and the texture of the feldspar suggests that a certain amount of recrystallisation has taken place. In

addition, many aegirine and amphibole grains appear to have suffered limited marginal replacement by albite.

Trends in pyroxenes from the Younger Granites:

In view of the lack of precise information about the composition of many of the calcium-rich pyroxenes from the granites, it is perhaps optimistic to attempt to discuss the compositional trends in the Nigerian pyroxenes. However, a certain amount of indirect information about changes in composition in the pyroxenes has been obtained from petrographic studies on the rocks, although such information must be used with caution.

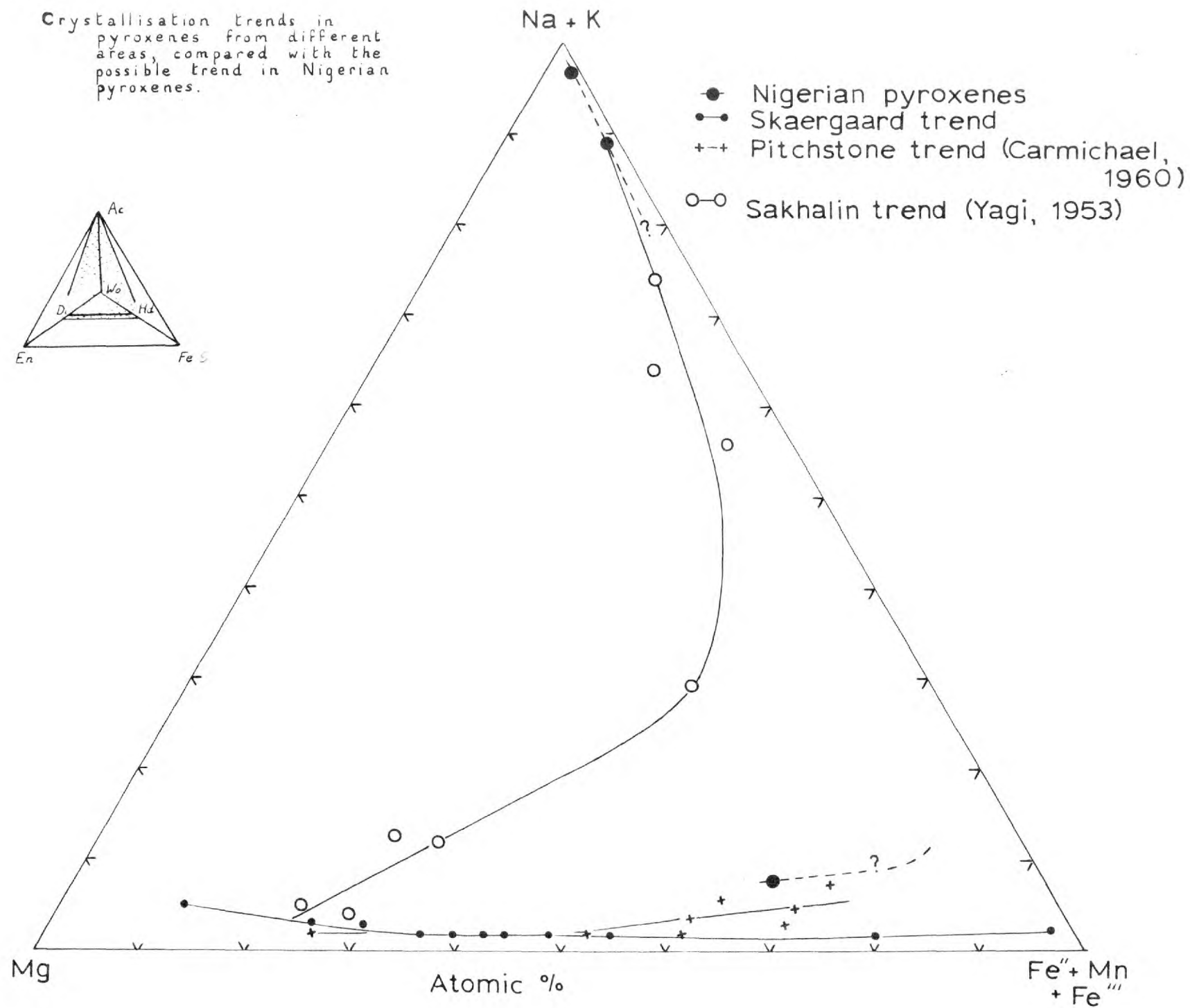
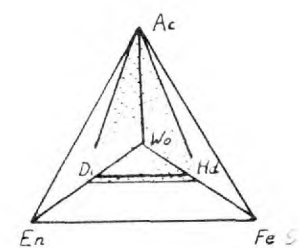
In PB.47, an amphibole-fayalite granite from Sara-Fier complex, a pale-green pyroxene occurs which has an extinction angle of 40° and this pyroxene is probably near hedenbergite in composition. Zoned pyroxenes occur in PB. 6 and PB.13, both of which are porphyries from the Liruei complex. In PB. 6 a small number of phenocrysts are present, some of which have cores that are pale pink or greenish in colour and outer zones which are pleochroic from emerald-green to deep emerald-green; this outer zonal material has a maximum extinction angle of 17° and it is presumably of sodic composition. The β value of the marginal material is greater than 1.738 but accurate measurement of β was not possible. In PB.13 the phenocryst cores again appear to be of hedenbergitic composition and they are rimmed by green aegirine which has a maximum extinction angle below 20° . The Memoir by Jacobson et. al. (1958) gives a β value of 1.741 and 2V of 63° for the hedenbergite core of the pyroxene from PB.13. It is probable that both these porphyries were intruded when the composition of their residual magmas had become enriched in soda. Rapid cooling, indicated by the fine-grained groundmass of each of the porphyries, prevented further reaction of the soda-rich residuum with the pyroxene phenocrysts and resulted in the deposition of aegirine, or soda-rich pyroxene, as marginal rims. Judging from the optical evidence it seems likely that the bulk composition of each of the pyroxenes from these porphyries would be that of sodic-ferrohedenbergite. Further support for this suggestion can be found in the nature of the amphiboles, A. 6 and A.13, that co-exist with the pyroxenes in these

porphyries. Both these amphiboles, which will be discussed more fully later, are sodic in composition and they occupy a position which is nearly intermediate between the calcium-rich and alkali amphiboles from the Younger Granites.

In Fig. 4 pyroxenes from several localities, including those from Nigeria, have been plotted in the manner suggested by Carmichael (1962) in order to indicate the degree of soda-enrichment shown by calcium-rich pyroxenes. It is possible that the calcium-rich pyroxenes from the Younger Granites follow a trend similar to that of the ferr-augites from the Icelandic pitchstones, although they are undoubtedly more sodic in composition than the latter. It is also probable that only limited solid solution between the end-members aegirite and hedenbergite is found in the Nigerian calcium-rich pyroxenes.

FIG:4

Crystallisation trends in pyroxenes from different areas, compared with the possible trend in Nigerian pyroxenes.



(2) The Amphibole Group:

General considerations of the formulae for amphiboles:

The formulae for the magnesium-rich end-members of the main amphibole sub-groups were derived hypothetically by Sundius (1946) from a consideration of possible substitutions in the formula for tremolite, $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ (or in its ferrous analogue actinolite $\text{Ca}_2\text{Fe}''_5\text{Si}_8\text{O}_{22}(\text{OH})_2$), but only the formulae for the alkali amphiboles, riebeckite and arfvedsonite, and one of the calcium-rich amphiboles, ferrohastingsite, need be considered here.

By substitution of Na_3Al for Ca_2Mg in the tremolite formula, Sundius obtained the formula for eckermannite, $\text{Na}_3\text{Mg}_4\text{AlSi}_8\text{O}_{22}(\text{OH})_2$, the ferrous analogue being arfvedsonite. If Na is substituted for Ca in the ratio 1:1 in the tremolite formula without filling the vacant space in the lattice, then valency adjustment must be made by substitution of Al for Mg in the Y-group and this leads to glaucophane, $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$, the ferrous-ferric analogue being riebeckite.

The only calcium-rich amphibole which is relevant here is pargasite, $\text{NaCa}_2\text{Mg}_4\text{AlSi}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$, the formula for which is arrived at by substitution of AlAl for Mg and Si and of NaAl for Si in the tremolite formula; the ferrous-ferric analogue of pargasite is ferrohastingsite.

In 1947, Miyashiro reclassified the alkali amphiboles and this classification differed in several ways from that of Sundius, the most important change in regard to the present discussion of Nigerian amphiboles being in his suggested formula for arfvedsonite, $\text{Na}_2\text{Ca}_{0.5}\text{Fe}''_{3.5}\text{Fe}'''_{1.5}\text{Al}_{0.5}\text{Si}_{7.5}\text{O}_{22}(\text{OH})_2$.

Amphiboles from the Younger Granites of Nigeria:

Amphiboles represent one of the largest mineral groups to be found in the Nigerian complexes and they have previously been divided on the basis of their optical properties and chemical composition into (a) calcium-rich amphiboles which occur in many of the early intrusions of granite and porphyry and which are usually referred to as "hornblende", and (b) alkali amphiboles which are found in the riebeckite granites and arfvedsonite granites and porphyries. In addition a small number of

so-called "soda amphiboles" have been recognised in a number of granites (Jacobson et. al. 1958).

Formulae of the amphiboles from the Younger Granites:

In the present discussion the following formulae have been used as a basis for classification of the Nigerian amphiboles:

- (a) Calcium-rich amphiboles: Ferrohastingsite, $\text{NaCa}_2\text{Fe}''_4\text{Fe}'''_2\text{Al}_2\text{Si}_6\text{O}_{22}(\text{OH})_2$
- (b) Alkali amphiboles: Riebeckite, $\text{Na}_2\text{Fe}'''_2\text{Fe}''_3\text{Si}_8\text{O}_{22}(\text{OH})_2$
 Arfvedsonite (Sundius), $\text{Na}_3\text{Fe}''_4\text{Fe}'''_2\text{Si}_8\text{O}_{22}(\text{OH})_2$
 " (Miyashiro), $\text{Na}_2\text{Ca}_{0.5}\text{Fe}''_{3.5}\text{Fe}'''_{1.5}\text{Al}_{0.5}\text{Si}_{7.5}\text{O}_{22}(\text{OH})_2$

The formulae of the alkali amphiboles have been calculated to 24 (O + OH + F) in the usual way, but calculation of the formulae of the ferrohastingsites has been made on the basis of 23 oxygen atoms as it was not always possible to determine H_2O^+ because of insufficient material.

(a) Calcium-rich amphiboles, $\text{NaCa}_2\text{Fe}^{II}_4\text{Fe}^{III}\text{Al}_2\text{Si}_6\text{O}_{22}(\text{OH})_2$:

Eight of these amphiboles have been analysed, their chemical analyses and optical properties being given in Table 7 and their formulae in Table 7b.

Chemical variations:

Variations in composition within the ferrohastingsites can be shown most simply by considering variations within the structural groups given by the general amphibole formula $\text{AX}_2\text{Y}_5\text{Z}_8\text{O}_{22}(\text{OH})_2$, where Z includes Al, Ti and Si; Y includes Fe^{II} , Fe^{III} , Mn, Mg, Li, Al, Ti, Zn, Cr, and Ni; X includes Ca, Na, K, Ba; (OH) includes F and Cl.

Z-group:

This group contains small tetrahedrally co-ordinated ions such as Si ($0.42\text{\AA}$), Al ($0.51\text{\AA}$) and Ti ($0.68\text{\AA}$). The inclusion of Ti in the Z-group in order to bring the total up to eight atoms is common practice when working out the formulae of amphiboles, but the presence of this large ion in tetrahedral co-ordination must impose a considerable strain on the amphibole lattice and it may be that Fe^{III} ($0.64\text{\AA}$) should be allotted to this group instead of Ti (Ernst, 1962).

The main features of the Z-group of the ferrohastingsites are the relatively high Si contents and the deficiencies in Al, which has a maximum value of 1.73 atoms in A.97. Fig. 5 shows that Si increases slightly, relative to the other tetrahedrally co-ordinated ions. Two other groups of genetically related hastingsites have been described previously; those occurring in granites and granite gneisses of the Adirondacks Region, New York, described by Buddington and Leonard (1953), and those from the alkali rocks of the Marangudzi Ring Complex, Southern Rhodesia, which have been discussed by Borley and Frost (1963). Compared with these hastingsites the Nigerian minerals are richer in silica and lower in alumina.

Y-group:

The ions that occupy structural sites of this group include Fe^{II} ($0.74\text{\AA}$), Mn ($0.80\text{\AA}$), Mg ($0.66\text{\AA}$), Fe^{III} , Al and Ti. One atom of Fe^{III} should be present in ferrohastingsites, but the range is from 0.44 atoms in A.38 to 0.96 atoms in A.71. This lack of Fe^{III} is partly

TABLE 7

Chemical analyses and optical properties of calcium-rich amphiboles

	A.38	A.48	A.96	A.97	A.45	A.51	A.47	A.71
SiO ₂	40.20	39.43	38.08	38.10	39.10	40.98	41.70	39.32
Al ₂ O ₃	8.32	8.65	7.67	8.97	8.47	8.63	4.61	9.39
TiO ₂	2.06	2.20	2.23	1.95	2.22	1.92	1.89	1.92
Fe ₂ O ₃	3.66	4.89	6.41	6.80	6.01	4.36	4.29	7.91
FeO	25.52	25.59	28.81	27.50	26.61	22.31	28.32	21.93
MnO	0.48	0.70	0.54	0.51	0.64	0.62	0.65	0.32
MgO	4.05	2.43	1.09	0.78	1.97	5.63	2.08	1.46
ZnO	0.09	0.14	n.d.	0.22	0.12	n.d.	0.17	n.d.
CaO	10.30	10.04	9.45	9.47	10.21	10.97	10.31	11.00
Na ₂ O	2.12	2.29	1.85	2.18	2.17	2.97	2.10	2.24
K ₂ O	1.33	1.61	1.52	1.69	1.48	1.22	1.42	1.49
P ₂ O ₅	0.26	0.21	nil	0.13	n.d.	n.d.	n.d.	n.d.
H ₂ O ⁺	0.98	1.1	0.65	0.58	n.d.	n.d.	n.d.	n.d.
H ₂ O ⁻	nil	0.01	nil	0.06	0.07	0.14	0.14	nil
F	0.48	0.29	0.58	0.58	1.13	1.12	1.85	3.02
Cl	0.66	0.81	1.98	0.72	n.d.	n.d.	n.d.	n.d.
Less O, for F, Cl	100.51	100.39	100.86	100.24	100.21	99.97	99.53	100.00
	0.35	0.31	0.69	0.41	0.47	0.47	0.78	1.27
	100.16	100.08	100.17	99.83	99.74	99.50	98.75	98.73
α'	1.687	1.702	1.705	1.704	1.701	1.699	1.703	1.695
γ'	1.707	1.702	1.718	1.721	1.718	1.712	1.725	1.711
γ'-α'	0.020	0.018	0.013	0.017	0.017	0.013	0.022	0.016
α'	Straw	Lt. straw	Pale buff		Lt. fawn	Fawn	Fawn	Fawn
γ'	Brownish-green	Deep olive green	Grey-green	Grey-green	Olive green	Olive green	Deep green-brown	Dull green-brown

TABLE 7(b)

Formulae of calcium-rich amphiboles, calculated on the basis of 23 oxygen atoms

	A.38	A.48	A.96	A.97	A.51	A.45	A.71	A.47
Si	6.428	6.370	6.274	6.239	6.404	6.285	6.361	6.753
Al	1.568	1.630	1.489	1.732	1.591	1.605	1.639	0.901
Ti	0.004	-	0.237	0.039	0.005	0.110	-	0.236
Z-group	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	-	0.019	-	-	-	-	0.151	-
Ti	0.243	0.267	0.039	0.201	0.220	0.157	0.233	-
Fe ^{III}	0.440	0.594	0.818	0.836	0.513	0.726	0.962	0.536
Fe ^{II}	3.352	3.458	3.876	3.766	2.915	3.578	2.966	3.930
Mn	-	0.076	-	0.007	0.041	0.066	0.044	0.020
Mg	0.965	0.586	0.267	0.190	1.311	0.472	0.352	0.514
Y-group	5.000	5.000	5.000	5.000	5.000	5.000	4.707	5.000
Ca	1.713	1.695	1.668	1.635	1.837	1.759	1.906	1.832
Na	0.657	0.717	0.590	0.691	0.597	0.676	0.702	0.674
K	0.271	0.330	0.320	0.352	0.244	0.303	0.307	0.301
Mn	0.064	0.024	0.075	0.063	0.041	0.021	-	0.072
Fe ^{II}	0.061	-	0.094	-	-	-	-	-
AX-group	2.766	2.766	2.747	2.741	2.719	2.759	2.915	2.879
Atomic ratio: (Fe ^{II} Mn)100 Fe ^{II} Mn Mg	77.6	85.8	93.6	95.2	69.3	88.6	89.5	88.5
Mol. ratio: Fe ^{II} :Fe ^{III}	7.6	6.0	4.7	4.4	5.8	5.0	3.0	7.4

FIG. 6 Variation in Ca, Al with Na, K, R⁴⁺ (where R⁴⁺ is Si or other quadrivalent ion)

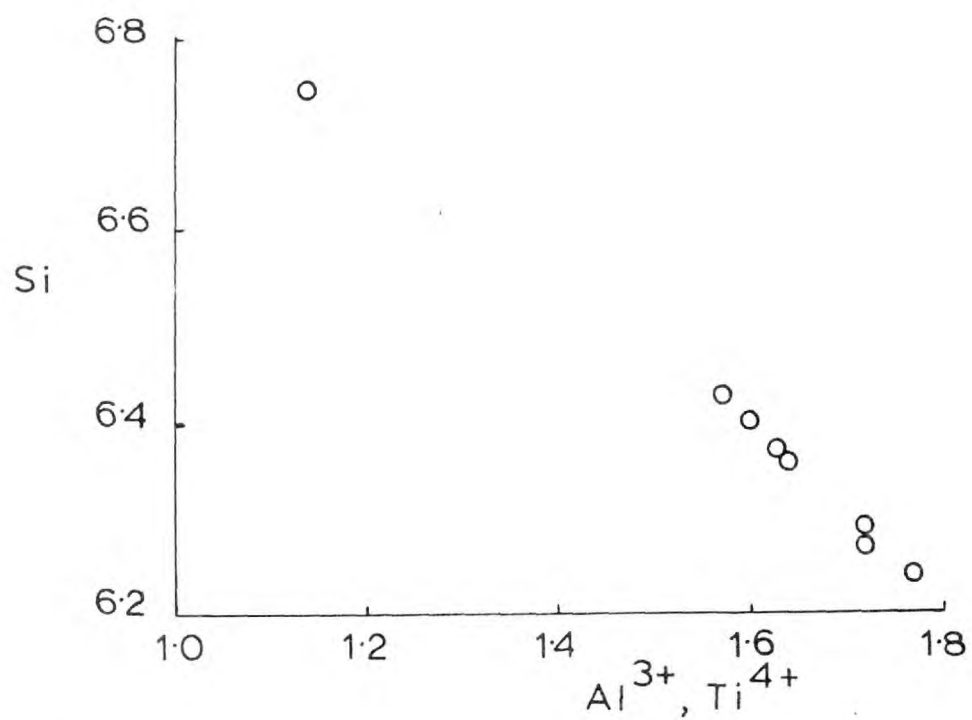
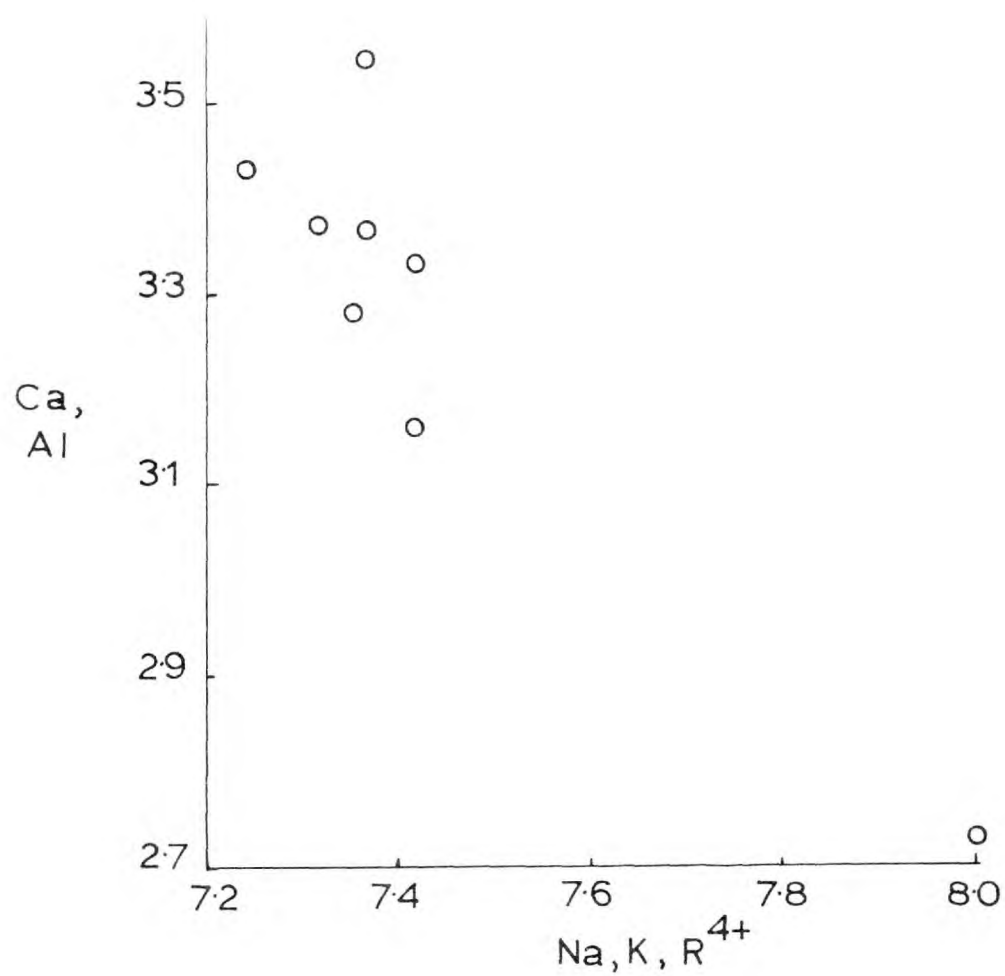


FIG. 5 Atomic variation in Si with variation in other tetrahedrally co-ordinated ions.

balanced by the presence of Ti in octahedral sites but there is no regular variation in Fe''' with Ti. Fe'' + Mn + Mg should total four atoms, but their actual totals lie between 3.362 atoms in A.71 and 4.536 atoms in A.47; this amphibole is low in Fe''' and has no Ti or Al present in octahedral co-ordination.

The most important substitution in this group is that of Fe'' for Mg, as shown by the large increase in the ratio (Fe'' + Mn)100: Fe'' + Mn + Mg (see Table 7b). Accompanying this increasing iron enrichment is an increase in Fe''' relative to Fe'' indicated by the decrease in the Fe''/Fe''' ratio from 7.8 in A.38 to 3.0 in A.71.

Reference to Table 7 will show that a small amount of zinc is present in a number of the ferrohastingsites and, although it is unimportant atomically, the fact that zinc has been found in these minerals is of considerable interest. Reports of Zn being present in silicate minerals in significant amount are not very common, the most comprehensive survey being that of Wedepohl (1953), who did not, however, report any zinc being present in ferrohastingsites or alkali amphiboles. Sundius (1946) gives an analysis of eckermannite from Norra Karr, Sweden, which includes 0.59% ZnO and Tauson and Kravchenko (1956) have reported the presence of zinc in hornblendes and biotites from Caledonian granitoids of the Susamin batholith of Central Tian-shan, but the authors considered the possibility of sub-microscopic blende being present in the minerals. X-ray work, by M.T. Frost of Manchester University, on the Nigerian amphiboles has not shown the presence of any zinc compound and it seems that the element is present as a normal lattice substitute for Fe''. A number of ferrohastingsites from the Marangudzi Ring Complex, already mentioned, have recently been analysed for zinc (by Dr. I.S.E. Carmichael) and the maximum content was only 550ppm.

AX-group:

This group includes large ions such as Ca (0.99Å), Na (0.97Å) and K (1.33Å), the alkali atoms having occupied the usually vacant (A) lattice sites. Small amounts of Fe'' and Mn have also been allocated to this group when the structural sites of the Y-group are full.

The Ca content of the minerals is always slightly less than the theoretical requirement of two atoms, the maximum calcium content being 1.906 atoms in A.71. There is only a slight variation in the alkali content and there is no regular increase in alkali with decrease in Ca. There is, however, a general decrease in Ca content with increase in Fe⁺⁺⁺ in the Y-group. Fig. 6 shows the variation in Ca, Al with variation in (Na,K)R⁴⁺ (where R⁴⁺ is any quadrivalent ion) in these amphiboles. The other groups of hastingsites mentioned previously by the author, from the Adirondacks Region and the Marangudzi Ring Complex, have higher Ca and Al contents than the Nigerian minerals, but the hastingsites from the Adirondacks show no systematic variation in Ca, Al content with (Na,K), R⁴⁺.

(OH)-group:

It has not been possible to determine H₂O⁺ or chlorine on several of these amphiboles, but fluorine has been determined on all of them and shows considerable variation in content. Where Cl was determined it was found to be high, particularly in A.96 which is a slightly altered mineral. The only comparable hastingsites are those from the Adirondacks Region, which contain an average of 0.5% Cl.

A point of interest in connexion with the ferrohastingsite analyses is the close similarity in chemical composition that exists between some hastingsites and the brown or yellowish-brown amphibole, barkevekite, found in many syenites and undersaturated rocks. Billings (1928) apparently distinguished barkevekite from members of the hastingsite group but did not denote brown hastingsites or alkali-hastingsites by any special names, and Troger (1952) used the name barkevekite for hastingsites with molecular percentages of Fe⁺⁺Fe⁺⁺⁺ between 50% and 75%. Wilkinson (1961) has pointed out that the composition of barkevekite is related to that of end-member ferropargasite, and Deer, Howie and Zussman (1962) have proposed the formula (Na,K)Ca₂(Mg,Fe⁺⁺,Mn,Fe⁺⁺⁺)₅-Al_{1.5}Si_{6.5}O₂₂(OH)₂ for barkevekite. This formula suggests an alumina content that is slightly too low for many barkevekites and it could also embrace many other members of the hastingsite-ferrohastingsite series, including several of those from the Nigerian granites, already

discussed.

Compositionally it is not always easy to decide what distinguishes barkevekite from femaghaastingsite or ferrohaastingsite; also, on the basis of their refractive indices, amphiboles that optically otherwise resemble haastingsites are sometimes referred to as barkevekites (Rees, 1960). The most distinctive features of the composition of many barkevekites are the high alumina and low water contents of the majority of them, and the low water content in particular may be of some significance, implying either formation under slightly anhydrous conditions or secondary release of hydrogen from the (OH)-group. Typically, barkevekites are found in the same types of undersaturated rock as green or blue-green haastingsite and they presumably form under essentially similar conditions of $P(O_2)$ and T . Undoubtedly one of the most interesting properties of barkevekites is their brown pleochroism and this cannot be simply related to any one aspect of their very variable chemistry. It was suggested by Ball (1941) that a high Ti content was responsible for the red-brown colour of some biotites, but that a high Ti content accompanied by high Mg resulted in brown biotite. Chinner (1960) also considered that the Ti content of some brown biotites was the main cause of their colour, with the ferric to ferrous iron ratio playing a minor part. However, although these explanations could be applied satisfactorily to a number of barkevekites they could not explain the colour of those barkevekites which are deficient in TiO_2 (as many of them are; see Wilkinson 1961). Other factors that may be important when considering the colour of these minerals are (a) the secondary oxidation of ferrous iron to ferric which might be accompanied by a colour change in the mineral and (b) the possibility that one or more of the cations occupies a different lattice site from that it normally occupies and that this affects the optical properties of the mineral (as Ti in tetrahedral co-ordination is known to affect the optical properties of pyroxene). The author suggests that the colour could be the result of Ti, or in some cases Fe^{+++} , occupying tetrahedral sites instead of Al, but this is a very tentative proposal, for the wide compositional range shown by barkevekites suggests that there may

no single explanation of their pleochroism.

Optical properties:

The major compositional trends in the ferrohastingsites are towards enrichment in Fe^{++} and increase in total iron, and these trends are accompanied by a slight decrease in Si content and minor variations in the contents of calcium and alkalis. Each of these variations should have some affect on the refractive indices, but it has proved difficult to show a close relationship between changes in the indices and any particular variation in composition.

Optical determinative curves for amphiboles were produced by Tröger (1952) and the sections of his curves for (V) and (α) relating to iron-rich hastingsites, are reproduced in Figs. 7(a) and (b) respectively. The refractive indices of the Nigerian ferrohastingsites have been plotted against their Mg and Fe^{++} contents on these figures, together with a number of other hastingsites and barkevekites from other areas. It is obvious that, except for imprecise work, the optical properties of amphiboles are of limited value in attempting to determine their compositions.

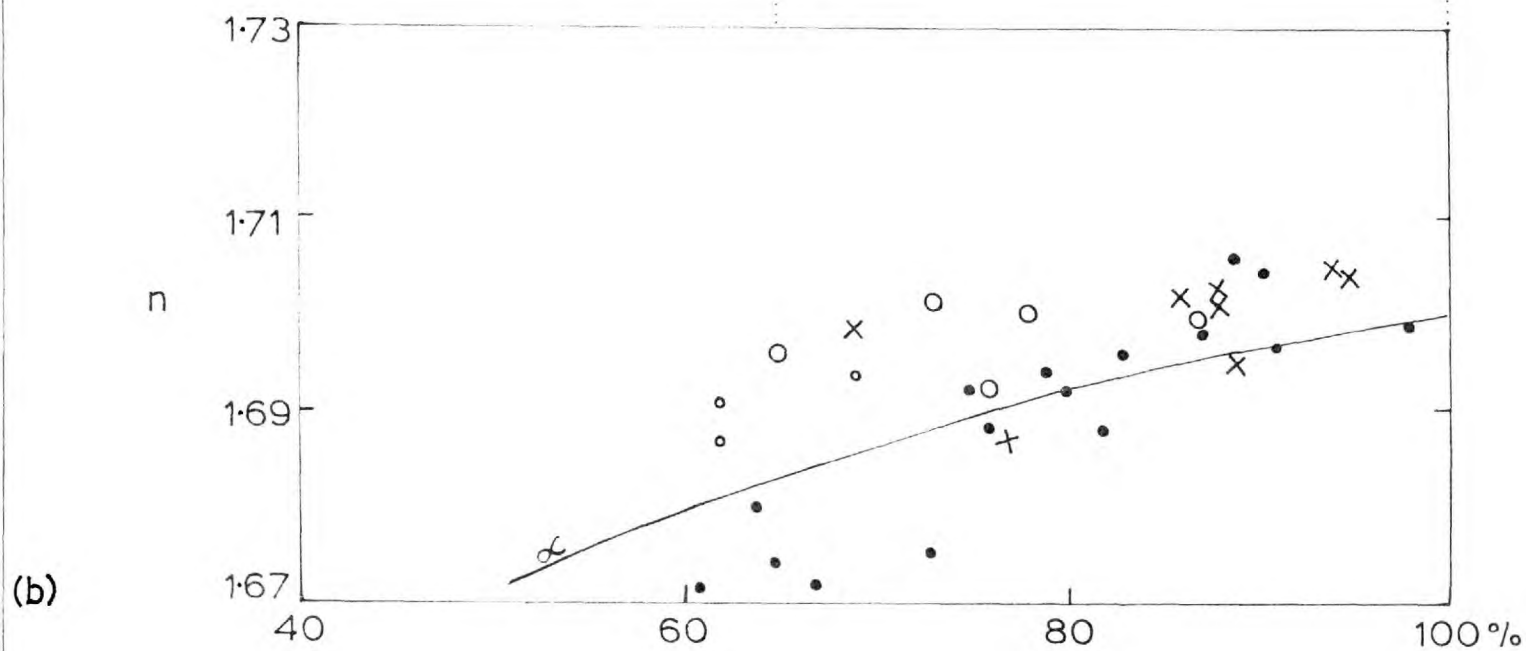
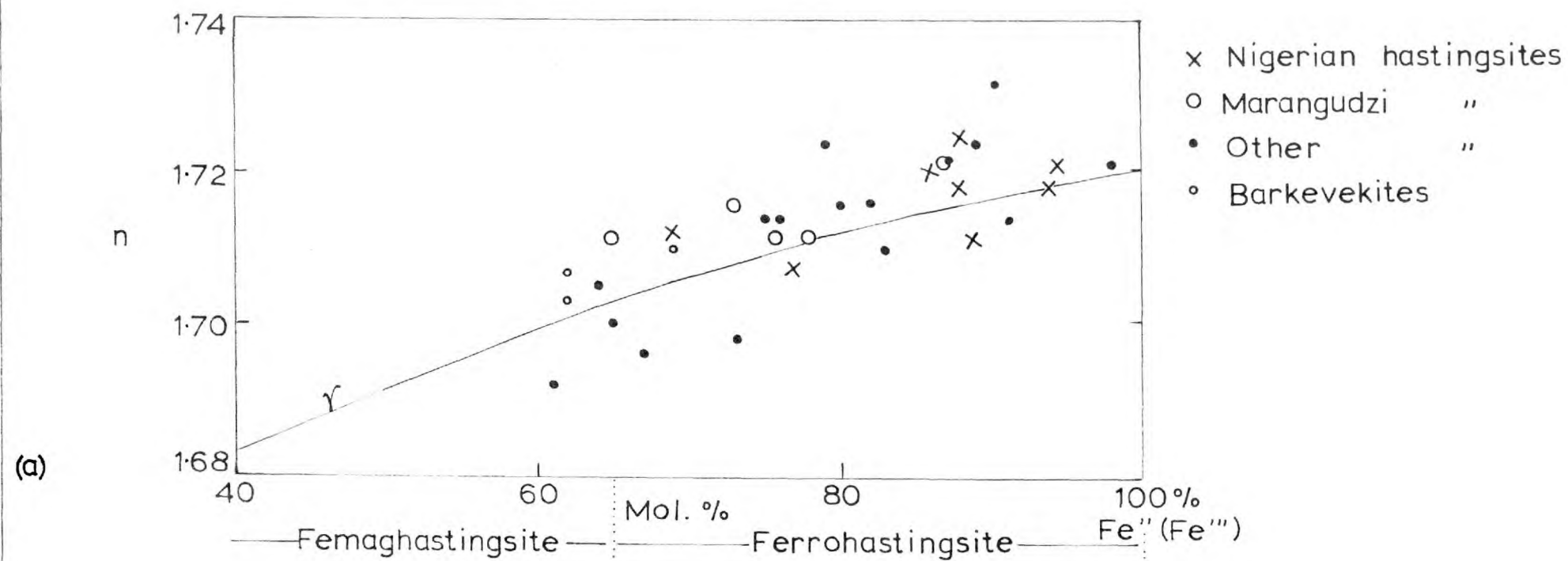
Unit-cell parameters:

The amphibole structure:

A detailed discussion of the amphibole structure is given by Bragg (1937) and only a brief summary is given here.

Amphiboles are chain silicates; structurally they consist of $(Si,Al)_4O_{11}$ tetrahedra that are linked together to give a chain of composition $\left[(Si,Al)_4O_{11}\right]_n$ (these chains have a width which is double that of the pyroxene chain $(Si_2O_6)_n$. Two of the $\left[(Si,Al)_4O_{11}\right]_n$ chains, with the apices of their individual $(Si,Al)_4O_{11}$ tetrahedra pointing inwards towards each other, are linked together by cations such as Fe^{++} , Mg, Mn, Fe^{+++} etc., and the two linked chains form the basic unit of the amphibole cell; a number of sites within the basic unit, other than those occupied by ions such as Fe^{++} , Mg, etc., are occupied by hydroxyl ions. These basic units are stacked one above the other and are repeated every $5.3\text{\AA}$, the latter distance being the length of the c-parameter of the unit-cell; the units are bonded together laterally and vertically by a

FIG: 7 (After Troger 1952) Optical determinative curves for hastingsitic amphiboles.



plane of large cations such as Na, K, and Ca which occupy the X-sites in the lattice, and also by large cations such as Na that can occupy the sometimes vacant A-sites.

The stacking of the basic units in the direction of the c-parameter is done in a manner that for most amphiboles produces a monoclinic cell with β approximately 104.7° , and the size of β is said to be largely governed by the size of the ion (Na, K or Ca) which occupies the X-sites (Whittaker, 1960). The general formula for amphiboles $AX_2Y_5Si_8O_{22}(OH,F)_2$, where A is usually Na or K; X is Na, K or Ca; and Y is usually Fe'', Mg, Mn, Fe''', Ti or Al, gives the composition of the ideal half unit-cell.

The unit-cell parameters of the ferrohastingsites are given in Table 8. Attempts to correlate changes in composition with changes in the unit-cell dimensions of these minerals have been partially successful, and the following points can be made.

a-parameter. The only substitution that can be related to a decrease in a is that of ferrous iron for Mg, and this is shown in Fig. 8.

b-parameter. A small increase in b can again be correlated with enrichment in Fe'', as shown in Fig. 9, and with an increase in total iron. The fairly close relationship between enrichment in ferrous iron and increase in total iron in the ferrohastingsites, and increase in the size of the b-parameter seemed to suggest that measurement of b might be a useful method of determining the iron content of amphiboles of this type, when chemical analysis was not practicable. However, M.T. Frost of Manchester who carried out the determinations of unit-cell parameters, points out (personal communication) that for a large number of samples the correlation between size of b and iron content is much poorer than is indicated in Fig. 9, and he also points out that Ca, in particular, has an effect on the size of the b-parameter.

c-parameter. A partial correlation exists between increase in Si and length of c.

β . The small decrease in Ca can be most nearly correlated with a decrease in size of β .

TABLE 8.

Unit-cell parameters of calcium-rich amphiboles. Space Group C2/m

Amphibole	a (Å)	b (Å)	c (Å)	β	a sin β	Volume (Å) ³
A.47	9.948	18.246	5.345	104.991	9.609	937.2
A.71	9.926	18.221	5.324	104.881	9.593	930.6
A.45	9.921	18.220	5.331	104.889	9.588	930.2
A.51	9.899	18.173	5.319	104.877	9.567	924.8
A.38	9.921	18.200	5.324	104.870	9.622	929.0
A.48	9.937	18.240	5.336	104.918	9.588	934.6
A.96	9.948	18.254	5.331	104.800	9.602	935.8
A.97	9.948	18.251	5.344	104.895	9.618	937.8

FIG: 8

Increase in a-parameter of unit cells of calcium-rich amphiboles, with increasing iron enrichment (atomic ratio)

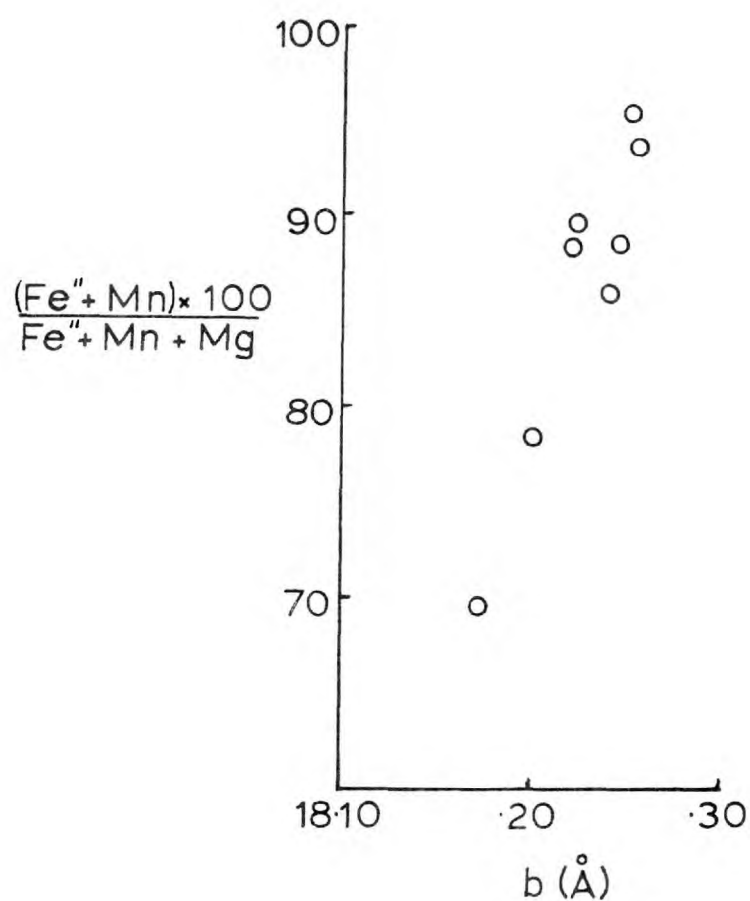
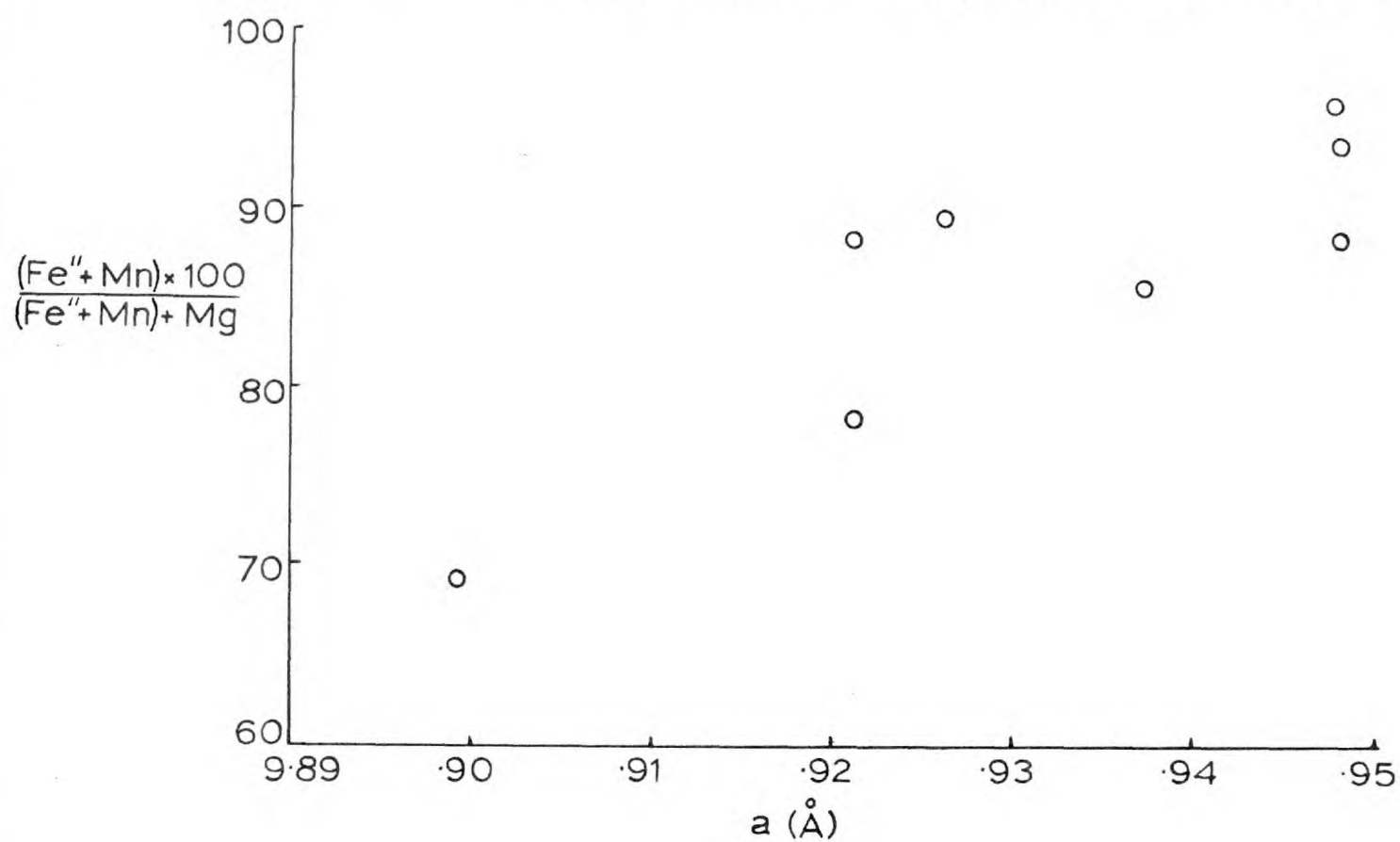


FIG: 9

Increase in b-parameter of unit cells of calcium-rich amphiboles with increasing iron enrichment.

(b) Alkali amphiboles:

Alkali amphiboles are widespread and abundant in the Nigerian Younger Granites and fourteen of them have been analysed by the author. Their analyses and optical properties are given in Table 9 and their formulae in Table 11.

Before considering in detail the chemical composition of the alkali amphiboles a number of essential differences between them and the ferrohastingsites, discussed previously, should be mentioned. In the ferrohastingsites the main trends were toward iron enrichment and increase in total iron and these were accompanied by slight changes in the ratios of Ca to alkalis and Si and Al. A considerable gap separates these calcium-rich minerals from the "intermediate" amphibole A.13, which is relatively enriched in Si, total iron and alkalis, and a further gap separates A.13 from the alkali amphiboles. An examination of the formulae of the latter indicates that many of them show the maximum possible enrichment in Fe²⁺ (relative to Mg) and alkalis, and a considerable enrichment in Si relative to Al. The substitution $Mg \rightarrow Fe^{2+}$ which was the main feature of the ferrohastingsites is no longer important in the alkali amphiboles. However, although they are deficient in magnesia and alumina, the alkali amphiboles show a number of interesting compositional variations and these will be considered, as in the ferrohastingsites, in terms of variations within the amphibole structural groups.

Zr-group:

Apart from Si, Ti and Al, some Zr ($0.79\text{\AA}$) and Fe³⁺ have had to be allotted to this group. The inclusion of Zr may not be completely justified as the radius of this ion is so much greater than that of Si, and it is also problematical whether Fe³⁺ can substitute for Si in amphiboles, although it undoubtedly does so in feldspars. (In a personal letter to the author, W.G. Ernst suggested that Fe³⁺ might be a more likely substitute for Si than either Zr or Ti, and this view is shared by other mineralogists and crystallographers).

The minerals show a gradual enrichment in Si relative to other tetrahedrally co-ordinated ions as will be seen from Fig. 10.

TABLE 9

Analyses and optical properties of alkali amphiboles

	R. 3	R. 7	R.20	R.50	R.57	R.58	R.63	R.64	R.65	R.85	R.30	R.79	R.92	A.37
SiO ₂	50.25	48.09	47.45	47.70	47.60	48.59	49.60	48.44	48.74	49.15	48.47	49.61	50.19	47.56
ZrO ₂	0.56	0.43	0.28	0.87	0.14	0.20	0.44	0.15	0.13	0.20	0.41	0.21	0.20	0.28
Al ₂ O ₃	0.26	0.60	0.66	1.15	0.86	0.92	0.34	0.10	0.36	0.95	0.59	0.27	0.24	0.88
TiO ₂	0.80	1.74	1.61	1.04	1.66	1.28	0.76	1.15	1.17	1.14	0.74	0.52	0.60	1.51
Fe ₂ O ₃	13.95	10.88	12.65	12.90	13.71	13.22	11.48	12.42	12.61	13.10	11.89	12.91	13.34	9.28
FeO	17.09	25.33	21.41	22.57	22.35	21.10	22.24	21.12	21.52	20.60	22.93	19.50	20.53	26.03
Li ₂ O (Photometric)	2.20	0.53	0.42	0.52	0.46	0.67	0.51	0.97	0.99	1.16	0.74	1.76	0.65	n.d
MnO	0.62	0.62	0.98	0.54	0.60	0.47	0.40	0.52	0.41	0.32	0.37	0.48	0.37	0.61
MgO	0.04	0.05	0.03	0.44	0.07	0.03	0.16	0.42	0.05	0.30	0.05	0.13	0.03	0.34
ZnO	0.93	0.43	0.33	0.50	0.59	0.56	0.64	0.62	0.64	0.64	0.47	0.47	0.78	0.26
PbO	0.18	n.d.	n.d.	n.d.	0.01	0.06	0.07	0.04	0.07	0.04	0.01	0.07	0.02	n.d
CaO	0.20	0.87	2.88	2.22	1.74	1.79	0.90	1.95	1.02	0.64	0.88	0.31	0.49	4.27
Na ₂ O	8.80	7.41	6.62	6.36	6.92	7.30	8.77	7.92	8.08	7.66	8.88	9.43	8.67	5.74
K ₂ O	2.20	1.01	1.82	1.14	1.20	1.62	1.70	1.68	1.75	1.96	1.60	1.65	1.89	1.15
P ₂ O ₅	0.16	0.08	0.08	0.07	0.02	0.05	0.04	0.04	0.03	0.04	0.01	0.13	0.04	0.20
H ₂ O +	0.4	1.3	1.7	1.7	1.6	1.4	1.1	1.1	1.3	1.3	1.0	1.1	1.3	1.5
-	0.09	0.15	0.22	0.12	0.05	0.12	0.06	0.03	0.07	0.10	0.08	nil	nil	0.09
F	3.31	1.03	1.40	1.31	1.4	1.61	2.20	2.33	2.06	2.17	2.20	2.48	2.00	0.56
Cl	0.18	0.12	0.07	0.05	0.09	0.04	0.08	0.01	0.10	0.16	0.03	0.09	0.06	0.40
Less O, for F, Cl	102.22	100.67	100.61	101.20	101.07	101.03	101.59	100.97	101.10	101.63	101.22	101.02	101.40	100.66
	1.43	0.46	0.61	0.56	0.61	0.69	0.94	0.96	0.88	0.96	0.93	1.06	0.85	0.33
	100.79	100.21	100.00	100.64	100.46	100.34	100.55	100.01	100.22	100.67	100.42	100.06	100.55	100.33
Trace elements ppm														
Lithium (Spec.) As Li ₂ O%	2.16	0.43	0.54	0.32	0.32	0.65	0.86	0.97	0.86	1.3	0.54	1.3	0.65	n.d
Copper	7	n.d.	n.d.	n.d.	7	8	9	3	7	39	4	8	11	n.d.
Nickel	5	n.d.	n.d.	n.d.	5	3	4	5	5	10	5	4	9	n.d.
Lead	1800	n.d.	n.d.	n.d.	114	550	710	374	694	390	85	674	214	n.d.
Zinc	7500	3500	2625	4000	4750	4500	5125	5000	5125	5125	3750	3875	6250	2125
α'	1.677	1.691	1.694	1.692	1.691	1.685	1.676	1.684	1.685	1.681	1.679	1.677	1.677	1.691
γ'	1.693-4	1.696	1.702	1.704	1.704	1.699	1.688	1.699	1.697	1.700	1.694	1.695	1.698	1.700
γ'-α'	0.016	0.005	0.008	0.012	0.013	0.014	0.012	0.015	0.014	0.019	0.015	0.018	0.021	0.009
α'	Indigo	Deep grn. blue	Deep blue	Deep blue	Indigo	Deep grn. blue	Indigo	Indigo	Indigo	Indigo	Indigo	Very deep blue	Indigo	
γ'	Lt. green yellow	Lt. straw	Yellow	Yellowish	Dk. yellow green	Greenish yellow	Lt. yellow green	Yellow green	Yellowish	n.d.	Yellow green	Pale grn. yellow	Lt. yellow green	

[illegible]

✓ R = total ions in the Y-group

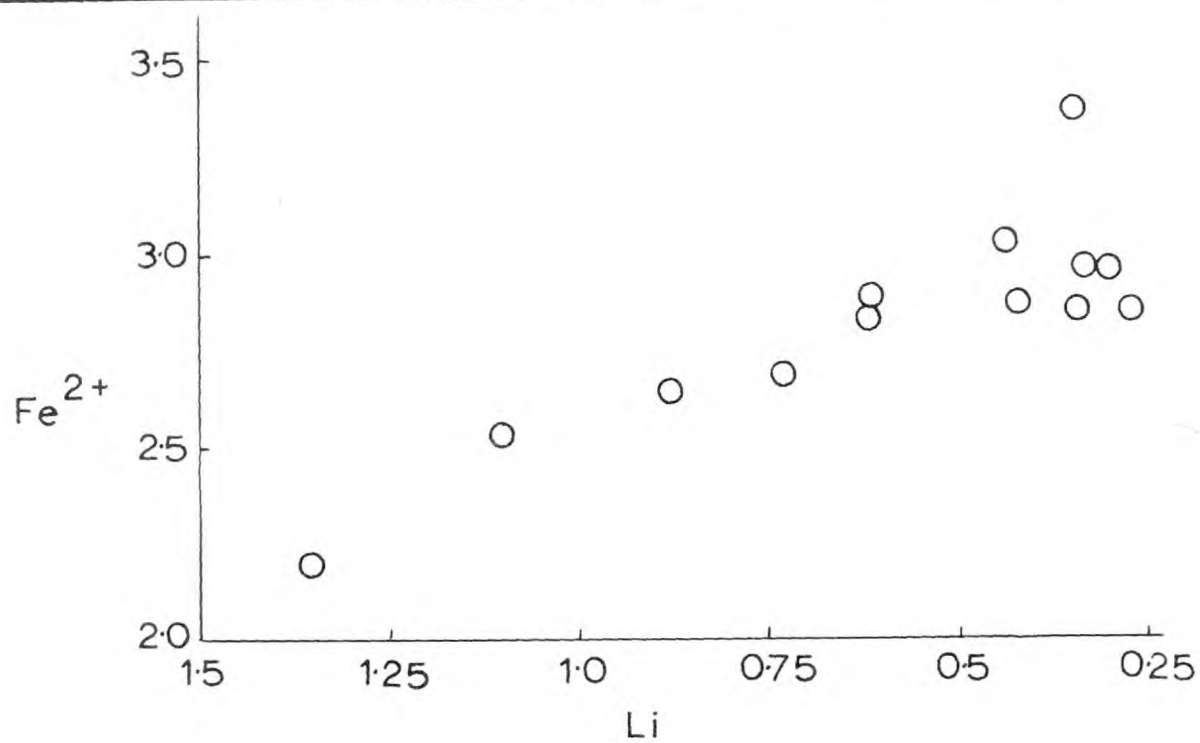


FIG. 11. Atomic variation in Fe^{2+} with variation in Li

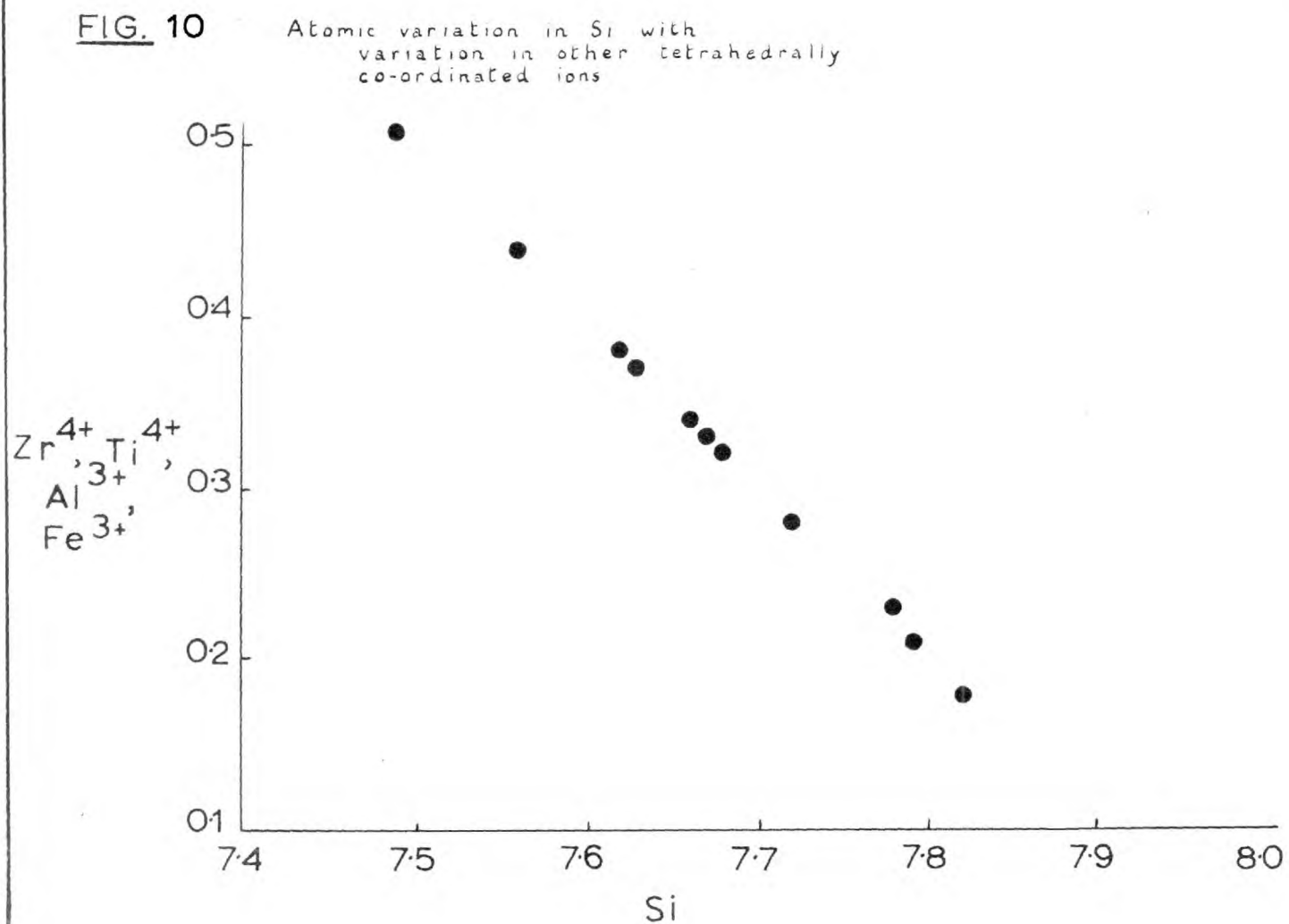


FIG. 10 Atomic variation in Si with variation in other tetrahedrally co-ordinated ions

Y-group:

The most important cations occurring in the Y-group of the alkali amphiboles are Fe^{2+} , Fe^{3+} and Li ($0.68\text{\AA}$), which is substituting for Fe^{2+} . Small amounts of a number of minor cations are also present, including Mn, Mg, Zn and, occasionally, Na, which has been allotted to this group when the AX-group structural sites are full. Na has been included in this group in preference to Ca as it is a slightly smaller ion and because excess Na ion is possibly a late entrant to the amphibole lattice. None of the minor cations shows any systematic variation in content with variation in Fe^{2+} or Fe^{3+} .

From the comparative point of view the most interesting of the minor substitutions for Fe^{2+} is that of Zn, although it reaches a maximum value of only 0.1 atom in A.3. The percentage of ZnO (average 0.59%) in these amphiboles shows a pronounced increase on the percentage present in the ferrohastingsites (average 0.15%) and corresponds to an enrichment of the parent rocks in zinc.

Undoubtedly the main variation within this group is the increasing substitution of Li for Fe^{2+} , shown in Fig. 11. The consequent decrease in Fe^{2+} results in enrichment in Fe^{3+} relative to Fe^{2+} and the $\text{Fe}^{2+}:\text{Fe}^{3+}$ ratio decreases from 3.12 in A.37 to 1.36 in A.3. See Fig. 13.

AX-group:

In the alkali amphiboles, in contrast to the ferrohastingsites, there is a definite correlation between decrease in the amount of Ca and increase in the amount of alkali present in this group, as reference to Fig. 12 will show. However, although most of the excess alkali appears to have occupied vacant lattice positions in order to make up for the electron deficiency caused by the decrease in Ca, there is a slight connexion between increase of alkalis and substitution of Li for Fe^{2+} in the Y-group. It will be noted that all the alkali amphiboles show partial or complete filling of the vacant lattice sites, with alkali.

(OH)-group:

Chlorine is a relatively unimportant substitute for (OH) in these amphiboles but fluorine shows a considerable range in content,

FIG. 12

Atomic decrease in Ca with
increase in alkali content of
alkali amphiboles.

1. Arfvedsonite (Sundius)
2. " (Miyashiro)

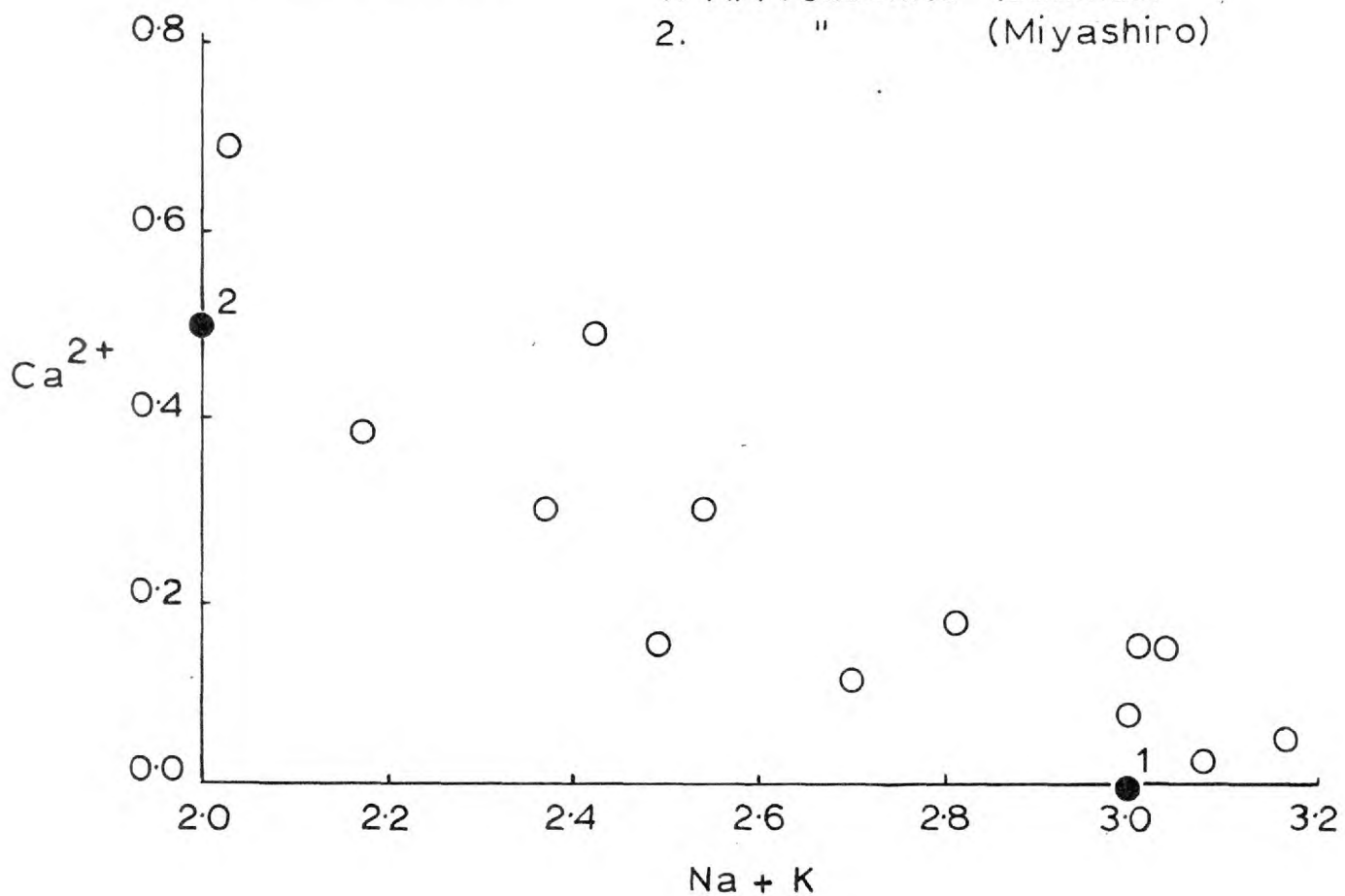
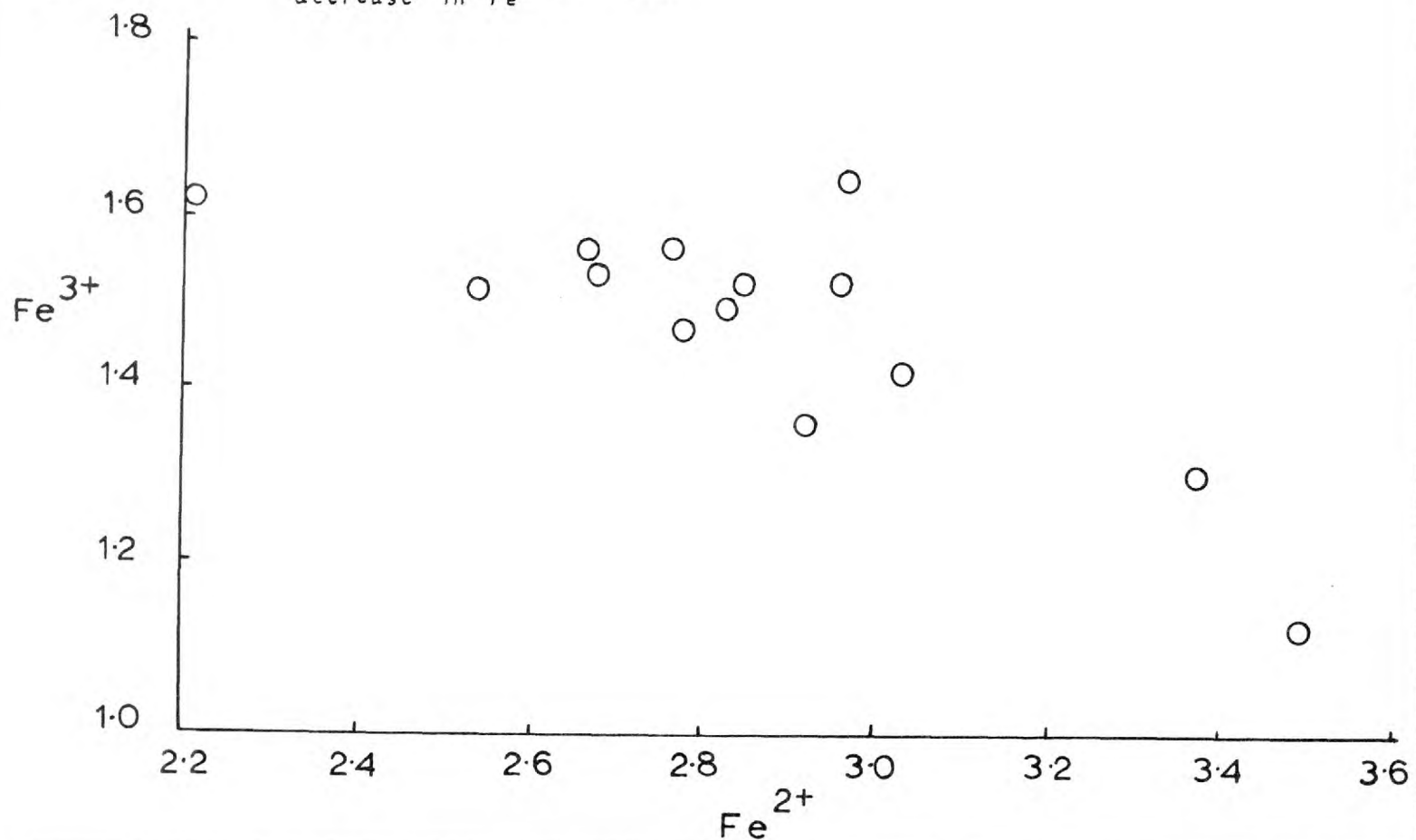


FIG. 13

Atomic increase in Fe^{3+} with
decrease in Fe^{2+}



as it did in the ferrohastingsites. In most of the minerals there is an excess over the theoretical maximum of two atoms for this group and it is possible that part of this excess represents analytical error in the determination of H_2O^+ .

Major variations in the alkali amphiboles:

The major substitutions in the alkali amphiboles are those of Ca for alkali and, to a lesser extent, Si for Al, and it is possible to show a regular decrease of CaAl with an increase in $(Na,K)R^{4+}$ (where R^{4+} is any quadrivalent ion). Fig. 14 shows that there is a good correlation between these two variations, the group of amphiboles having a trend that lies between the "extremes" of arfvedsonite composition as represented by the Miyashiro and Sundius formulas. It is obvious from Fig. 14 that arfvedsonites with formulae close to those of both Miyashiro and Sundius can be found in alkali granites, and it is also obvious that none of the amphiboles analysed approximates the formula of the theoretical riebeckite, which has also been plotted on this figure. The $Fe^{++}:Fe^{+++}$ ratios in the amphiboles are much more variable than in the formulae of Miyashiro or Sundius, but this is not an uncommon feature of natural arfvedsonites and riebeckites. In view of the fact that all the Nigerian alkali amphiboles contain appreciable amounts of calcium and show partial or complete filling of the vacant lattice sites with alkalis, the author suggests that the Nigerian minerals would be more correctly described as riebeckitic-arfvedsonites or arfvedsonites than as riebeckites. Ernst (1962) has already suggested that a small number of Nigerian riebeckites are more correctly described as fluorarfvedsonites.

A large proportion of the magmatic iron-rich alkali amphiboles that have been described as riebeckite are actually riebeckitic-arfvedsonites, in the sense used by the author, and very ^{few} show a close approach to the formula for end-member riebeckite. The two analysed igneous minerals that closely approach the composition of end-member riebeckite are: the riebeckite from a felsite dyke associated with biotite granite in Shetland, described by Phemister, Harvey and Sabine (1950), and the riebeckite from granite-pegmatite associated with the Quincy, Massachusetts,

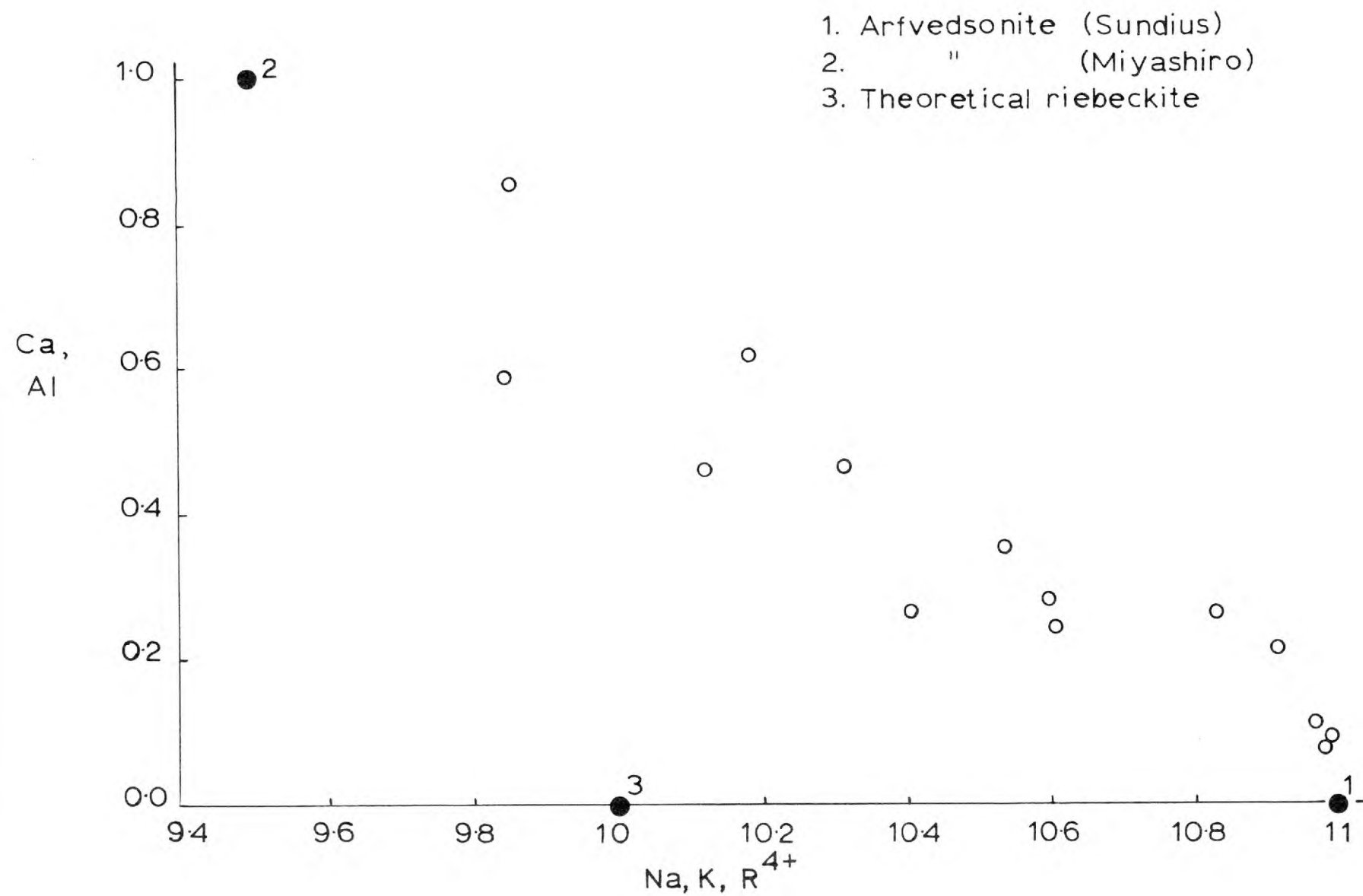


FIG.14 Atomic variation in Ca, Al with variation in alkali and quadrivalent ions

gradodiorite, discussed by Palache and Warren (1911). The type riebeckite from Socotra discussed by Sauer (1888) has an extremely high ferric iron content (28.3%) and contains no alumina or titania; the mineral was not analysed for water or fluorine and, as the analytical total is 99.98%, it would seem that a new analysis of this riebeckite is required.

Optical properties of the alkali amphiboles:

The strong absorption, high dispersion, and very small size of grains that must be used, make any optical work on alkali amphiboles extremely difficult, and the accuracy of the refractive indices given in Table 9 is not better than ± 0.003 . The sign of elongation of the minerals was always found to be negative but the optical sign could not be determined. Determination of $2V$ was generally impossible but where any attempt could be made to measure the angle it was between 70° and 80° .

A close correlation of optical properties with chemical composition of the alkali amphiboles does not appear to be possible but some general comments on the optical data can be made. Of the more common major constituents of the minerals, the alkalis, ferrous and ferric iron, and calcium, all affect the refractive indices to some degree. Calcium and the alkalis (which replace Ca in the X-group) have opposite effects on α' and γ' , the indices showing a general decrease with decreasing Ca and increasing alkalis, whilst increases in both Fe^{++} and Fe^{+++} can be correlated to some extent with an increase in γ' . Obviously the lack of very close correlation between increases in the elements mentioned and changes in α' and γ' can be partly explained by the low accuracy of refractive index determinations, but the lack of correlation may also be explained by the presence in the lattice of some less common ions, more particularly by the presence of F and Li. Increases in both these elements cause a general decrease in α' and γ' but increases in either F or Li can be correlated more closely with a decrease in α' than a decrease in γ' .

There is no doubt that although high refractive indices usually belong to the more iron-rich alkali amphiboles, only an approximate

idea of the composition of these minerals can be obtained from optical data because of the pronounced effects that such ions as F and Li have on optical properties.

Mention has been made in the section on petrography of the fact that the alkali amphiboles do not always show extinction in ordinary light in sections parallel to (010); this phenomenon is common in these amphiboles and has been discussed by Eskola and Sahlstein (1930), Iwao (1939), Yagi (1953), Sahama (1956), and by Shoda (1957). Eskola and Sahlstein, and Sahama, concluded from optical and X-ray work, that arfvedsonite consisted of an intergrowth of two amphiboles, but Shoda (1957) examined arfvedsonite from Kansanri, Korea, and concluded that the anomalous optical properties were due to elliptic polarisation of light caused by the strong absorption of the mineral. X-ray work, carried out by M.T. Frost of Manchester University, on single crystals of several of the Nigerian amphiboles, does not indicate any intergrowth of two amphiboles.

Unit-cell parameters:

Unit-cell parameters of the alkali amphiboles are given in Table 11b, and it will be immediately obvious that all the parameters are smaller than the corresponding ones for the ferrohastingsites. The main reasons for the large decreases in size of the parameters across the gap that separates the calcium-rich from the alkali amphiboles appear to be:

1. A substantial increase in Fe^{III} ($0.64\text{\AA}$) relative to Fe^{II} ($0.74\text{\AA}$) which can be correlated with a diminution in b . This trend counteracts the general trend toward an increase in b with increasing iron enrichment in the amphiboles.
2. A sharp increase in Na ($0.97\text{\AA}$) relative to Ca ($0.99\text{\AA}$) which can also be correlated with decrease in b and, to some extent, in a . This is probably a more important cause of the decrease in b than (1) above.
3. A large increase in Si ($0.42\text{\AA}$) relative to the other, larger, tetrahedrally co-ordinated ions is accompanied by a contraction in the c-direction, but the correlation is not close.
4. The change in amount of Ca present in the amphiboles is mainly responsible

TABLE 11(b)

Unit-cell parameters of alkali amphiboles. Space Group C2/m

Amphibole	a(Å)	b(Å)	c(Å)	β	a sin β	Volume (Å) ³
A. 3	9.810	17.943	5.307	103.833	9.525	907.0
A. 7	9.865	18.066	5.326	103.790	9.581	921.2
A.20	9.841	18.036	5.318	103.739	9.560	922.0
A.50	9.839	18.087	5.334	103.782	9.556	921.9
A.57	9.806	18.047	5.329	103.710	9.527	916.2
A.58	9.824	18.061	5.332	103.773	9.542	918.9
A.63	9.846	18.006	5.313	103.734	9.564	915.0
A.64	9.824	18.006	5.320	103.744	9.542	914.0
A.65	9.837	18.033	5.321	103.676	9.558	917.1
A.85	9.825	17.995	5.321	103.703	9.550	917.1
A.30	9.830	18.015	5.319	103.699	9.559	916.0
A.79	9.813	17.954	5.310	103.662	9.535	909.0
A.92	9.837	18.014	5.321	103.712	9.557	916.1
A.37	9.898	18.128	5.319	104.055	9.602	925.8

for the decrease in the size of β .

There is a less pronounced continuation of these trends within the alkali amphiboles causing further changes in unit-cell dimensions, and these changes are accentuated by other ionic substitutions not considered previously. The most important variations will be mentioned briefly:

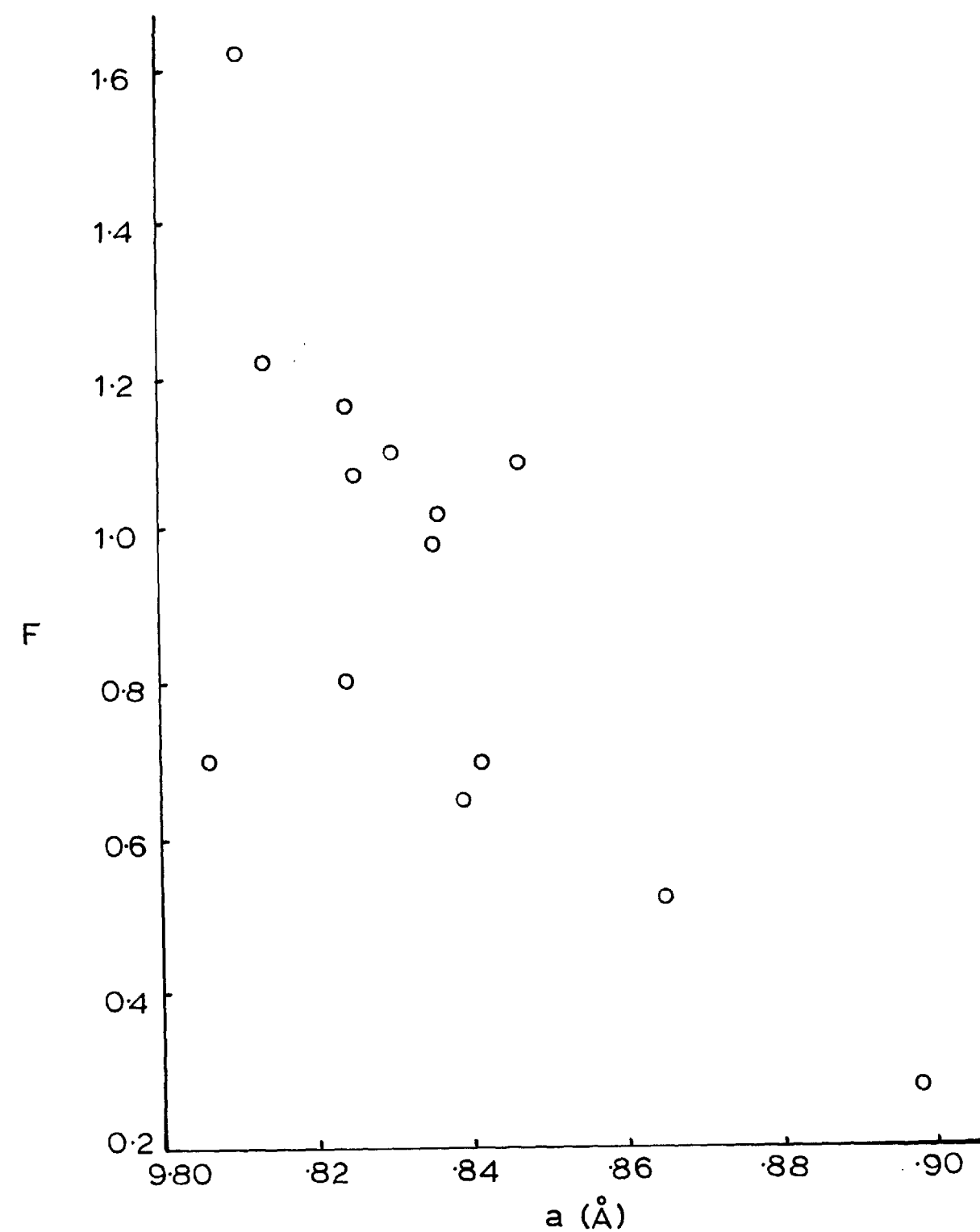
- a. A change in the length of a cannot be closely correlated with any of the major ionic substitutions, but it does decrease slightly as Ca decreases and as F increases relative to (OH), as shown in Fig. 15(a).
- b. A shortening in the b-direction can be correlated with a decrease in Ca, shown in Fig. 15(b), and with a decrease in the amount of total iron present, shown in Fig. 16(a). This decrease in total iron is mainly the result of the substitution of Li (0.68Å) for Fe²⁺, and the effect of this substitution on the length of b is shown in Fig. 15(c).
- c. Decrease in the length of c can be related to an increase in the amount of Si present in the minerals, as shown in Fig. 16 (b).

Cell volume. There is a gradual decrease in the volume of the unit-cells of the alkali amphiboles which, of course, can be correlated with any of the variations in composition already mentioned, but Fig. 16(c) shows only the combined effect that increases in Si and F have on cell volume.

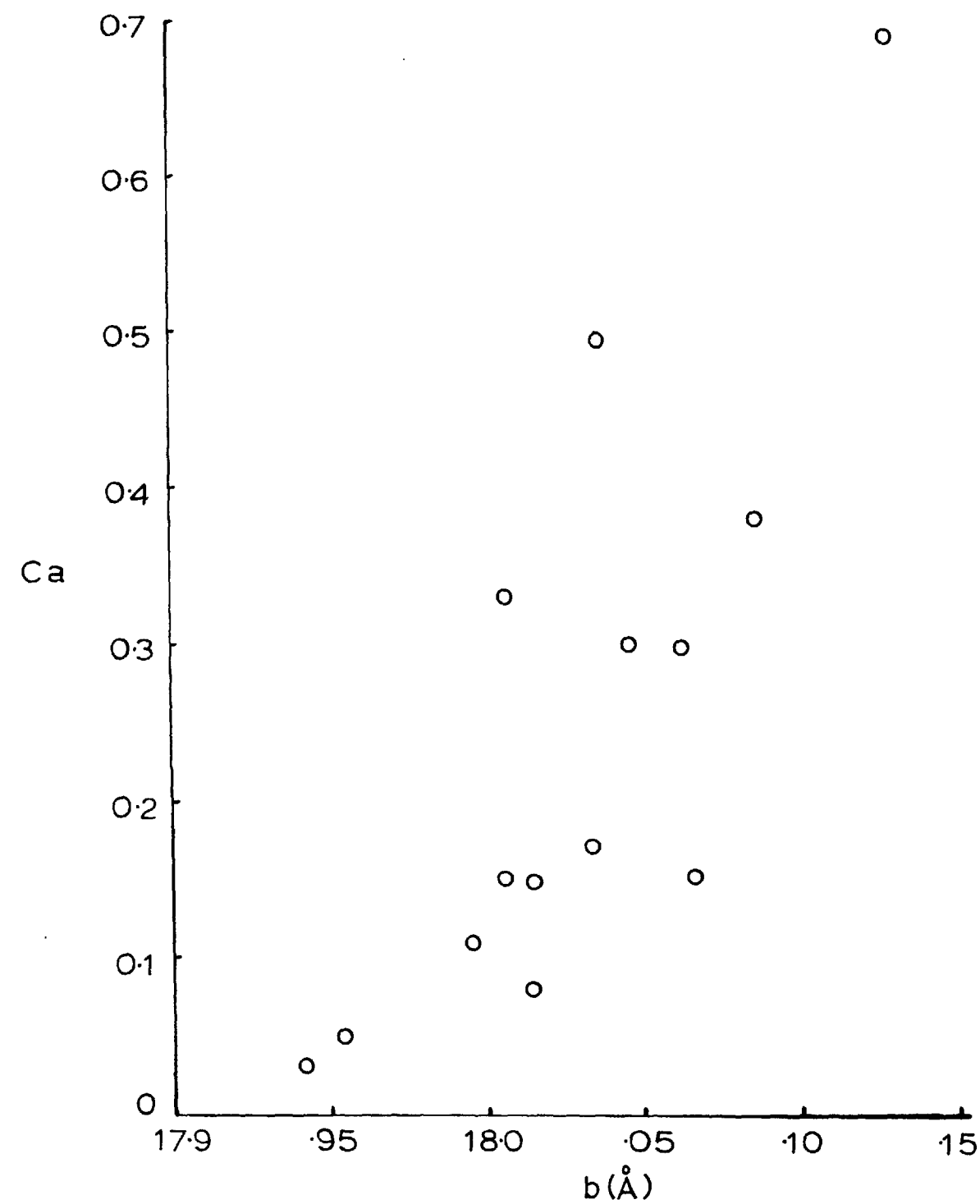
Fig. 17 shows the gradual decrease of β with decrease in Ca content of the ferrohastingsites and the intermediate and alkali amphiboles.

FIG: 15 Correlation of changes in unit cell parameters with atomic variations in chemical composition of alkali amphiboles.

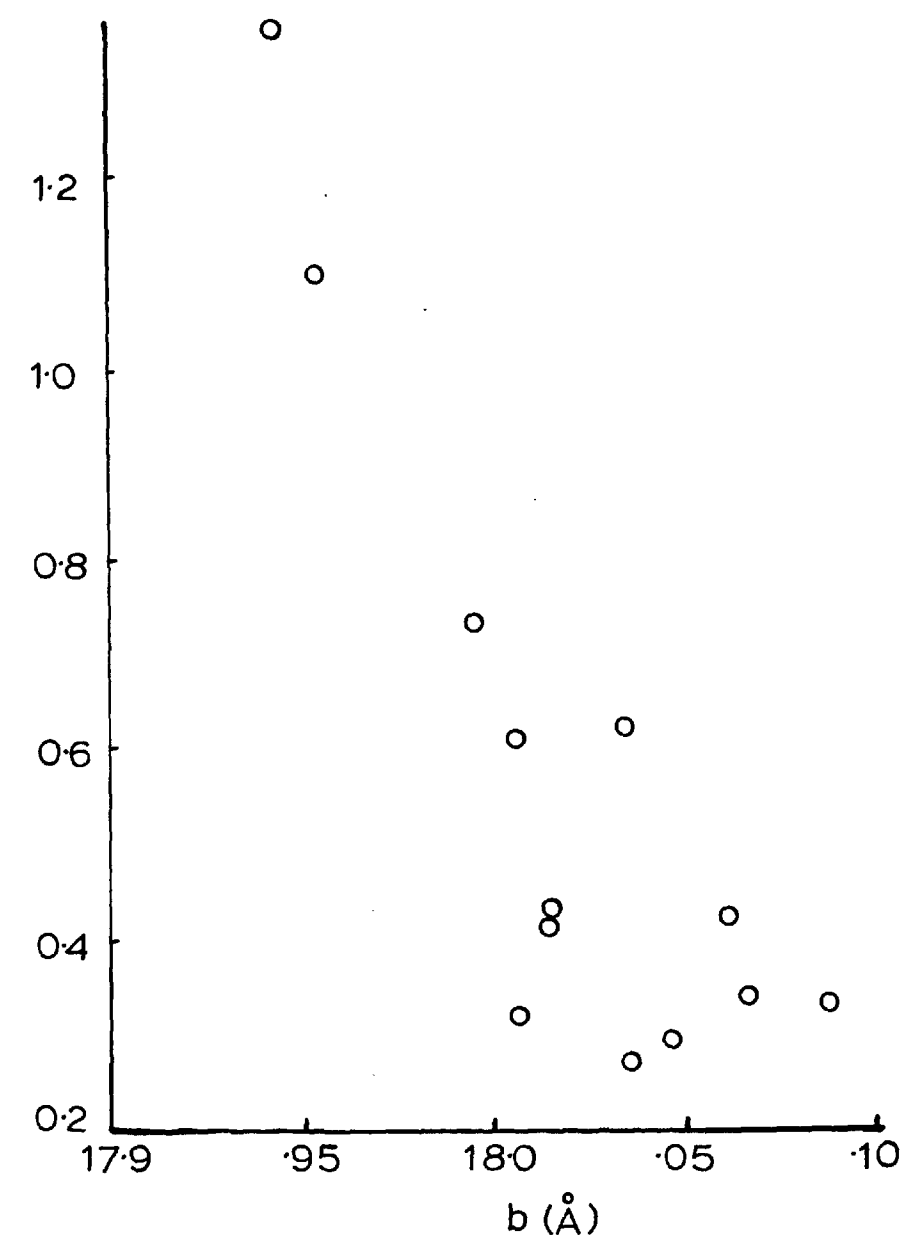
(a) General decrease in length of $a(\text{\AA})$ with increase of F.



(b) General decrease in length of $b(\text{\AA})$ with decrease in Ca.

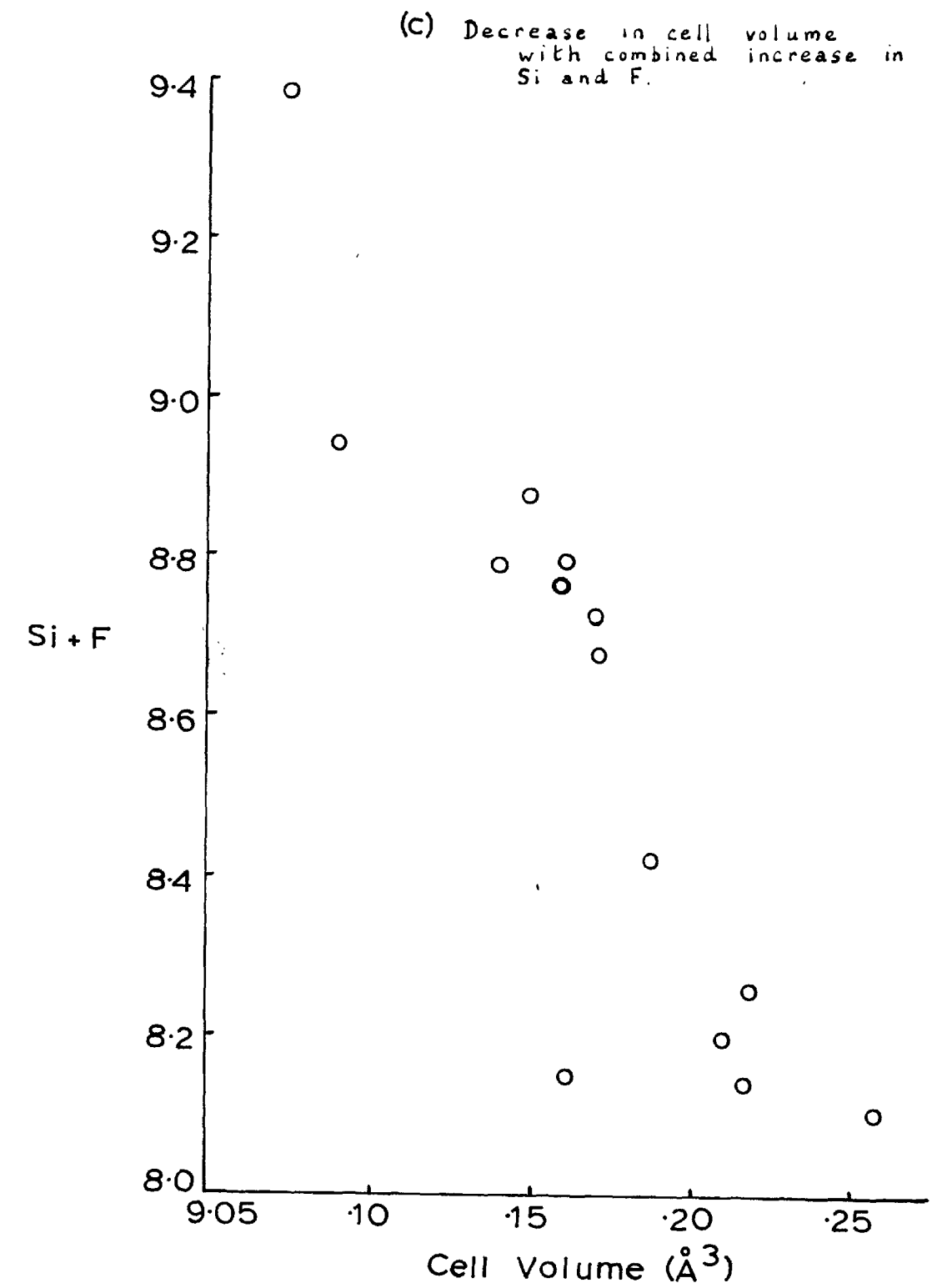
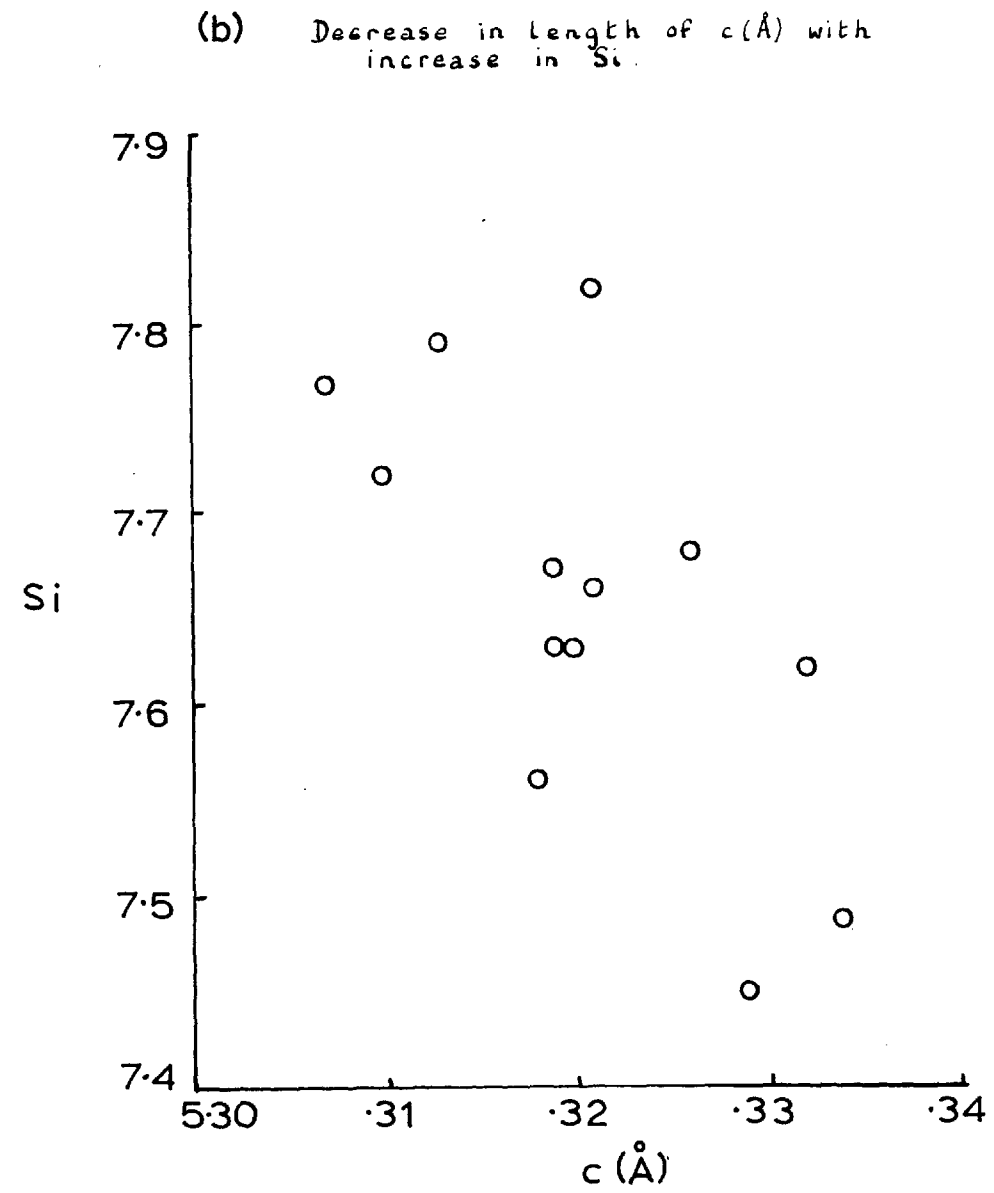
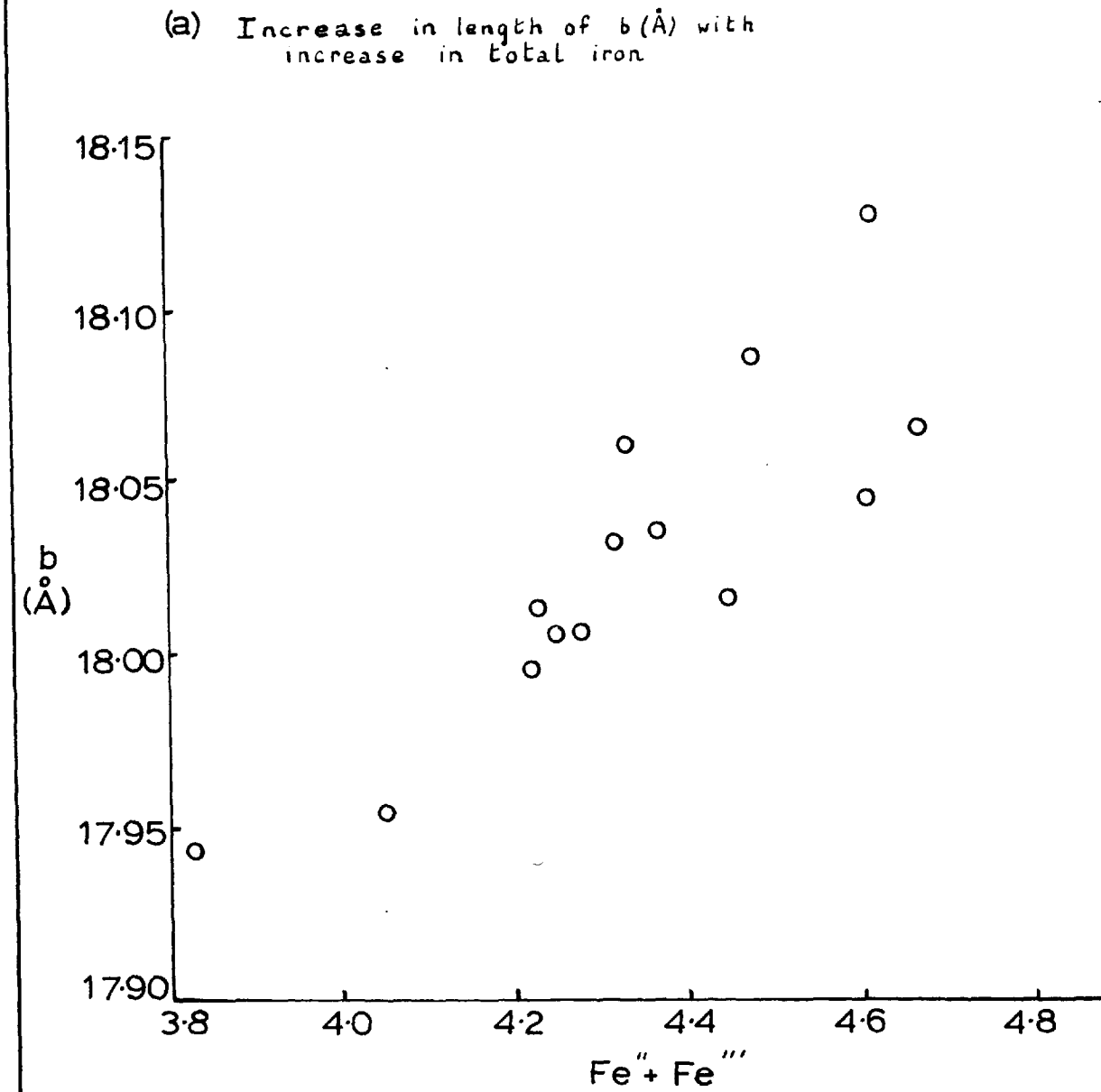


Li



(c) Decrease in length of $b(\text{\AA})$ with increase in Li.

FIG:16 Correlation of changes in unit cell parameters with atomic variations in chemical composition of alkali amphiboles.



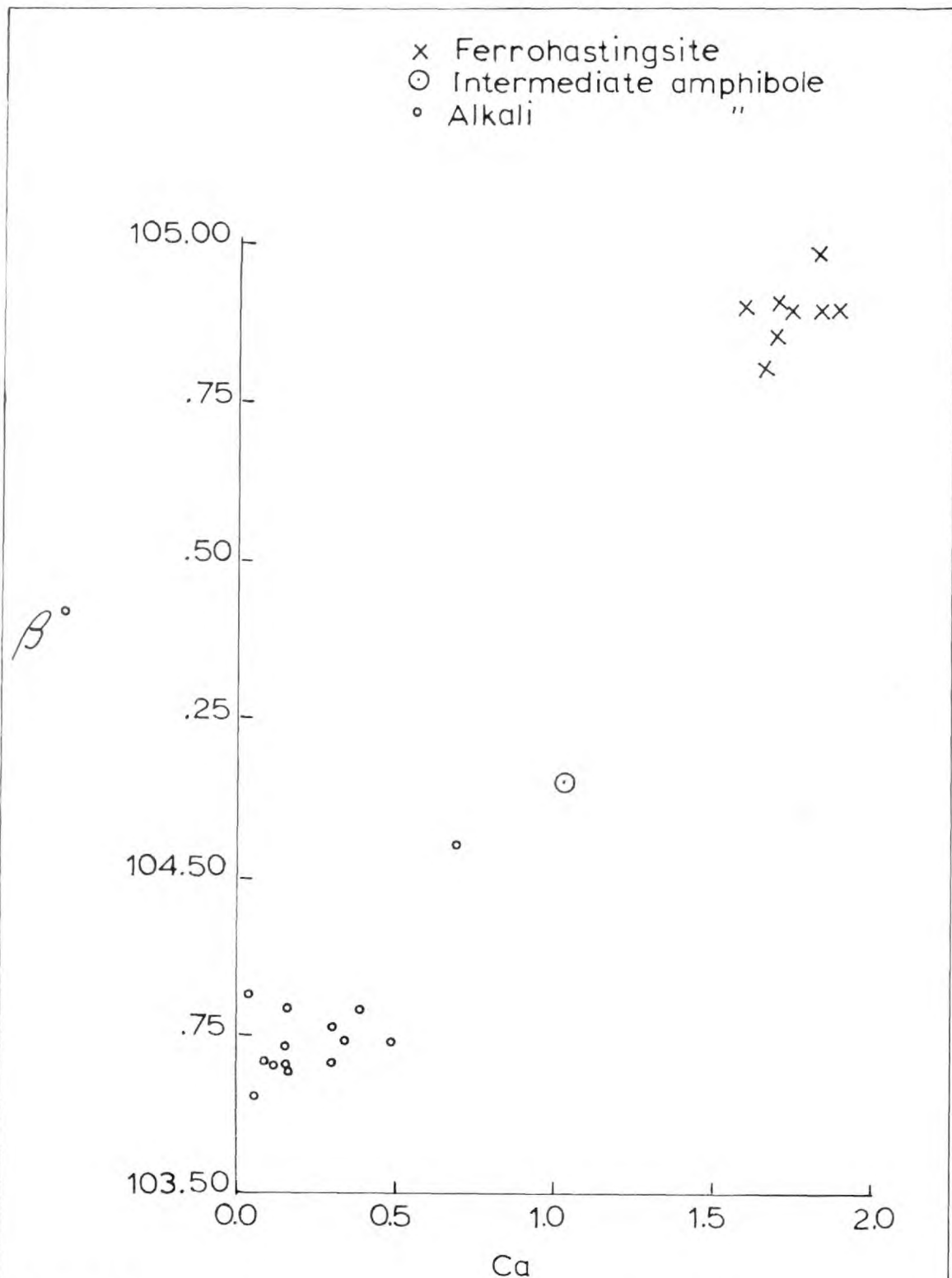


FIG: 17 General increase in β° with atomic increase in calcium, in analysed amphiboles.

(c) "Intermediate amphiboles";

Discussion of the intermediate amphiboles has been postponed until now so that their composition can be better compared with the compositions of the ferrohastingsites and alkali amphiboles previously discussed. Table 12 gives an analysis of A.13 and a partial analysis of A. 6, two amphiboles which come from porphyries belonging to the Liruei complex.

Amphiboles have been reported in the past (Billings, 1928) which could not be placed either in the hastingsite group or in any of the alkali amphibole sub-groups. Similarly A.13 and A.6 cannot be placed in a particular amphibole sub-group, although their low alumina, moderate alkali and high ferrous iron contents make them slightly closer in composition to the alkali amphiboles than to the ferrohastingsites of the Nigerian granites. Optically they also bear a strong resemblance to the alkali amphiboles, being bluish in colour and having lower refractive indices than the ferrohastingsites. The unit-cell parameters of A.13 are also intermediate in most respects between those of the ferrohastingsites and alkali amphiboles, as can be seen from Tables 8, 11(b) and 12. Considering all these factors the author suggests that these amphiboles provide some evidence that there is at least partial solid solution between the ferrohastingsites and alkali amphiboles from the Nigerian Younger Granites.

TABLE 12

Data for intermediate amphiboles

	Analyses		Formula of A.13 Calculated to 23 oxygen atoms
	A.13	A. 6	
Si ₁₀	45.57	46.02	(Si 7.564
Al ₂	1.89	0.90	Z (Al 0.363
Al ₂ 3			(Ti 0.073
Ti ₁₀	1.43	1.33	Total 8.000
Fe ₂	3.73	6.70	(Ti 0.100
Fe ₂ 3			(Fe''' 0.456
FeO	31.38	33.20	Y (Fe'' 4.262
MnO	0.68	0.62	(Mn 0.093
MgO	0.30	n.d.	(Mg 0.072
CaO	5.90	n.d.	Total 4.983
Na ₂ O	4.54	4.85	AX (Ca 1.026
K ₂ O	1.18	1.40	(Na 1.428
H ₂ O +	n.d.	n.d.	(K 0.243
-	0.13	n.d.	Total 2.697
Less O, for F	101.57		
	1.62		
	99.95		
Mol. ratio: Fe''':Fe'''	9.3	5.4	Unit-cell parameters of A.13
$\gamma \alpha'$	1.693		(a 9.923
$\gamma' - \alpha'$	1.701-2		o (b 18.180
	0.008-9		(c 5.319
α'	Pale straw		β 104.150°
γ'	Bluish-yellow		a sin β 9.622
	green		Vol. (A) ³ 930.5

(3) Biotite group:

Biotites occur in the amphibole-biotite, biotite and, although rarely, riebeckite granites from the Nigerian ring complexes; the biotites analysed by the author have come from the first and last of these intrusive groups. Biotites from these two types of granite are characterised by high iron contents, as a result of which they often have intensely strong absorption and high specific gravities. alteration of the biotites to hydrous biotites, by deuteric or hydrothermal solutions, is also common and the altered minerals are sometimes green in colour.

Composition of natural iron-rich biotites:

Iron-rich biotites are considered to be of three possible kinds (Eugster and Wones, 1962):

(a) Trioctahedral micas of general formula $K[Fe^{2+}_{3-x}(Fe^{3+}Al)_x]^{vi} - [(Fe^{3+}Al)_1 + xSi_{3-x}]^{iv}O_{10}(OH)_2$, which contain three cations in octahedral sites.

(b) Oxybiotites which contain less than two hydrogen atoms in the unit-cell formula.

(c) Trioctahedral micas which are solid solutions between micas of type (a) and dioctahedral micas such as muscovite, $KAl_2AlSi_3O_{10}(OH)_2$, ferrimuscovite, $KFe^{3+}_2AlSi_3O_{10}(OH)_2$, and ferriceladonite, $KFe^{3+}Fe^{3+}Si_4O_{10}(OH)_2$, in which there are two octahedral cations.

There are several end-members in the iron-rich biotites but the one that is of most relevance to the analysed biotites is annite, $KFe^{2+}_3(AlSi_3)O_{10}(OH)_2$, which forms a solid solution series with phlogopite, $KMg_3(AlSi_3)O_{10}(OH)_2$. In all these natural biotites there is, of course, limited replacement of the divalent cations by trivalent or quadrivalent cations.

Formulae of the analysed biotites:

The formulae of the analysed biotites, including the two altered hydrous biotites B.45 and B.36, have been calculated on the basis of $12(O + OH)$, and they are given together with the analyses in Table 13. Calculation of formulae of hydrous biotites can be made in several ways:

TABLE 13

Chemical analyses of biotite and formulae, calculated to 12(O + OH + F)

	B.45	B.36	B.51	B.87	B.29	B. 1	B.57
SiO ₂	33.10	30.72	35.94	35.36	35.14	37.38	35.40
Al ₂ O ₃	9.77	11.54	11.71	10.90	6.44	11.89	19.50
TiO ₂	2.96	3.04	3.33	3.04	2.87	1.84	2.45
Fe ₂ O ₃	12.19	11.62	5.00	3.76	4.40	4.38	0.27
FeO	24.43	26.49	23.91	31.38	34.92	28.65	31.17
Li ₂ O	n.d.	n.d.	n.d.	n.d.	n.d.	0.77	n.d.
MnO	0.40	0.64	0.50	0.65	0.53	0.41	0.42
MgO	1.95	0.15	6.35	1.06	0.43	0.22	n.d.
CaO	2.37	1.70	1.65	n.d.	0.97	0.16	n.d.
Na ₂ O	0.41	0.44	0.42	0.97	0.74	0.39	0.60
K ₂ O	5.43	4.35	6.95	9.04	8.92	8.78	9.78
H ₂ O +	5.55	8.27	4.15	3.74	3.12	1.84	n.d.
-	1.94	0.27	0.03	n.d.	0.06	0.67	n.d.
F	n.d.	n.d.	n.d.	n.d.	2.97	4.36	n.d.
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	0.09	n.d.
Less O, for F					101.03	101.94*	
					1.04	1.86	
	100.55	99.68	99.94	99.90	99.99	100.08	

(*Includes S and CO₂ 0.11%)

Ref. index

	B.45	B.36	B.51	B.29	B. 1
Si)	2.641	2.372	2.808	2.947	3.01
Al) iv	0.921	1.053	1.078	0.637	0.99
Fe ⁱⁱⁱ)	0.438	0.575	0.114	0.272	-
Total	4.000	4.000	4.000	3.856	4.00
Ti {	0.177	0.176	0.196	0.181	0.11
Fe ⁱⁱⁱ {	0.294	0.101	0.180	-	0.26
Fe ⁱⁱ { vi	1.634	1.714	1.562	2.456	1.93
Mn {	0.027	0.042	0.033	0.037	0.03
Mg {	0.232	0.017	0.738	0.052	0.03
Li {	-	-	-	-	0.25
Total	2.364	2.050	2.709	2.726	2.61
Ca	0.203	0.142	0.138	0.086	0.01
Na	0.063	0.064	0.064	0.120	0.06
K	0.553	0.428	0.643	0.954	0.91
Total	0.819	0.635	0.845	1.160	0.98
OH	2.951	4.272	2.164	1.749	0.99
F				0.650	1.11
Cl					0.01

(a) On the basis of 12 (O + OH) as has been done by the author.

(b) On the basis of 11 atoms of oxygen, the content of the ideal half unit-cell. If this method is used the water content of the biotites is ignored, which can be useful as water determinations on hydrous biotites are not always reliable.

(c) On the basis of the method proposed by Brown and Norrish (1952). These authors assume that the excess water in hydrous biotites is present in interlayer sites as the oxonium ion (H_3O^+) and that calculation of the number of such ions present in the unit formula is necessary. Although the last method is considered by the authors to give a better idea of the unit-cell contents than other methods, the present author has used (a) as the resulting formulae can be compared with those for the unaltered biotites.

In the formulae in Table 13, Al and, if necessary, Fe''' have been included in tetrahedral co-ordination. The position of Ti in biotites is apparently unknown but it has been included in the octahedral sites, following Foster (1960), although Chinner (1960) has excluded Ti from both octahedral and tetrahedral sites (on the grounds mentioned above, that the position of Ti in biotites is not known). The problem of where to place Ti in the biotite formula creates a slight difficulty with B.29, the ferruginous biotite, which has a small deficiency of tetrahedral ions. Unless it can be assumed that complete filling of tetrahedral sites is not essential, some Ti should presumably be allotted to these sites; Deer, Howie and Zussman (1962) include Ti in tetrahedral co-ordination in one biotite formula, but these authors state that there is no reason to assume that the tetrahedral sites must always be filled.

Composition of the biotites:

(i) Altered hydrous biotites:

B.45 and B.36 have both been subject to alteration and this is reflected in their high water contents. Schwartz (1958) suggests that early hydrothermal alteration of biotite may involve recrystallisation of brown biotite phenocrysts to aggregates of small biotite grains, and such small aggregates occur in a number of biotite-bearing rocks from the Younger Granite complexes. Ti is also believed to be removed from

biotite during early stages of alteration. Later stages of alteration include removal of Mg^{++} and iron, as shown by muscovite or sericite in association with biotite; both Schwartz and Walker (1949), who discussed alteration of soil biotites, think that oxidation of ferrous iron to ferric is also likely to occur during the alteration of biotite. Schwartz also points out that when abundant chlorite is produced then K^+ ions will be leached from the biotite and replaced by $(OH)^-$ ions.

B.45 obviously represents a comparatively early stage of alteration which involved replacement of K^+ ions by hydroxyl ions and the high ferric iron content of this biotite suggests that there has also been secondary oxidation of ferrous iron to ferric. It is difficult to decide whether any Mg has been removed from B.45 as although the magnesia content of this biotite is low, it is comparable with that of the co-existing amphibole A.45. B.36 is a green mica which shows more extreme replacement of K^+ ions and it seems likely that the very low magnesia content of this biotite is at least partly due to removal of Mg^{++} ions. Ferric iron is again high and the mineral is low in silica. It would probably be better to regard B.36 as a secondary mineral after biotite, rather than merely as an altered biotite like B.45.

(ii) Unaltered biotites:

Complete or partial analyses have been made of four unaltered biotites, B.51 and B.87 from hornblende-biotite granites, B.29 from the biotite-rich facies of a biotite-riebeckite granite, and B.57 from a riebeckite granite.

B.51 is a low potash biotite with a composition somewhere between annite and phlogopite, although slightly nearer to the annite end of the solid solution series. The low potash content is apparently a primary feature of the mineral, and in this respect it compares with several other biotites listed by Foster (1960) and Deer, Howie and Zussman (1962). B.87 is closer to annite in composition than B.51 and it also shows enrichment in alkalis and a decrease in alumina content. B.29 is a ferruginous biotite (containing less than 0.1 atom Mg in the half unit-cell) that is slightly richer in ferrous iron than any of the ferruginous biotites given by Eugster and Wones (1962). However, in the

biotites listed by these authors there is an average octahedral occupancy of 2.8 atoms compared with 2.7 atoms for B.29. The alkali content of B.29 compares with that of B.87 but the alumina content is much lower. As the ferric iron content of B.29 is also low there is a deficiency of ions in the tetrahedral sites of this biotite. Another partial analysis given in Table 13 is of B.57, a micaceous mineral of uncertain type which is a minor constituent of PB.57, a riebeckite granite. This mineral is light-coloured with a maximum absorption direction opposite to that of normal biotites, and it was thought originally to be an astrophyllite. The partial analysis, however, is that of an iron and alumina-rich biotite of a type unusual in the amphibole-bearing granites from the Younger Granite complexes. Biotite B.1 (Table 13) is a biotite from the Liruei biotite granite, the analysis having been taken from Jacobson et. al. (1958); like B.29 and B.87 it is an iron-rich biotite.

General features of the compositions of the analysed biotites:

Only a few general comments are possible on such a mixture of altered and unaltered minerals. Ignoring B.36, the analysed biotites appear to be trioctahedral micas of type (c) mentioned at the beginning of this discussion and, with the exception of B.57, were probably all originally members of the phlogopite-annite solid solution series. The unaltered minerals show decreases in calcium and magnesium, and increases in alkali and Fe⁺⁺ contents. Si increases relative to Al but this is largely due to an actual decrease in alumina content of the biotites. All the completely analysed minerals have ferric iron occupying tetrahedral sites in the lattice. There is no consistent variation in Fe⁺⁺:Fe⁺⁺⁺ ratios in the minerals, but there are too few analyses at present for any conclusions to be drawn from this.

MINOR SILICATE AND NON-SILICATE MINERALS:

(1) Cossyrite (aenigmatite):

Cossyrite is a relatively uncommon silicate mineral, although it is an important phenocryst in obsidians from the island of Pantelleria. Optically it is distinguished by a deep reddish-brown colour and high refractive indices (α greater than 1.79, γ 1.87), and chemically it is characterised by high total iron and titania. Although once considered to be an amphibole its membership of that group is now thought doubtful.

Fleischer (1936) presented optical and analytical data relating to a number of cossyrites and proposed a formula $\text{Na}_4\text{Fe}''_9\text{Fe}'''_2\text{Ti}_2\text{Si}_{12}\text{O}_{42}$ for the mineral. More recently Carmichael (1962) discussed the composition of cossyrite occurring in two obsidians from Pantelleria, and suggested that the formula $\text{Na}_4(\text{Fe}'', \text{Ti})_{11}\text{Si}_{11}\text{O}_{37}$ gives a closer indication of their composition than does the original formula of Fleischer. Yagi (1953) has also reported the presence of cossyrite in monzonites and syenites of the Morotu District, Sakhalin.

Cossyrite from the Younger Granites of Nigeria:

Cossyrite has been separated from PB.20, an aegirine-riebeckite granite from Liruei, and it is also present in PB.47, an amphibole-fayalite granite from Pankashin. The mineral is a very minor constituent of both these granites and its presence in the rocks was only revealed during mineral separation.

The analysis and optical properties of cossyrite from PB.20 are shown in Table 14 together with the analyses of two cossyrites from Pantelleria and the "average" of fourteen analyses of cossyrite from other localities, given by Yagi (1953). Compared with cossyrite from other areas the Nigerian mineral is poor in silica, alumina and lime and slightly enriched in titania and magnesia, and it is closer in composition to the "average" cossyrite than to either of the cossyrites from Pantelleria. The composition of the cossyrite from PB.20 shows a close approach to that of the theoretical end-member cossyrite (of the rhönite-cossyrite series postulated by Fleischer, 1936), particularly in its paucity of lime and alumina.

TABLE 14

Analyses and optical properties of cossyrite

	C.20	Av.	2A	3A	Theoretical	
					Fleischer	Carmichael
SiO ₂	39.71	40.14	41.02	40.97	39.82	41.54
TiO ₂	10.23	8.40	8.92	8.83	8.82	10.04
Al ₂ O ₃	0.13	1.80	0.94	0.89		
Fe ₂ O ₃	3.27	5.32	1.31	1.19	8.82	
FeO	37.03	33.17	38.84	38.86	35.70	40.63
MnO	1.20	1.96	1.16	1.08		
MgO	1.49	1.10	0.07	0.54		
CaO	0.20	1.15	0.45	0.55		
Na ₂ O	6.88	6.01	7.36	6.93	6.84	7.79
K ₂ O	0.24	0.26	0.06	0.08		
H ₂ O +	n.d.	0.62	-	nil		
-	n.d.	-	-	0.07		
	100.38	99.93	100.13	99.99	100.00	100.00

The relationship of cossyrite to other ferromagnesian minerals is rather obscure, although Carmichael (1962) has suggested that it might be formed by the reaction of fayalite and ilmenite (or ulvöspinel) with a soda-rich liquid. This suggestion was based on his observation that when cossyrite is present in significant amount in the obsidians from Pantelleria, the percentages of fayalite and ilmenite are considerably diminished. Such a reaction relationship could possibly be invoked to account for the occurrence of cossyrite in the Nigerian granites, for although the assemblage fayalite + ilmenite + cossyrite is presumably in equilibrium in PB.47, the amount of cossyrite present is negligible. In PB.20 cossyrite is more abundant and it occurs with aegirine and riebeckite only.

(2) Iron-titanium oxides:

Opaque minerals are most abundant in the more basic rocks from the Nigerian ring complexes, and particularly so in the gabbros. In the amphibole-fayalite and amphibole-biotite granites and porphyries the modal amount of opaque minerals is rarely greater than 1% and is generally less than 0.5%. The biotite and riebeckite granites contain only scattered grains of opaque minerals and these minerals constitute an insignificant percentage of the rocks.

Reflected light studies:

A number of polished rock sections and concentrates of iron-oxides were examined by the author:

The greatest concentration of opaque minerals was seen in PB.100, the Mama Gabbro, a rough estimate of their modal percentage being between 5% and 10%. The majority of opaque mineral grains in this gabbro are idiomorphic against the gangue minerals. Examination of the opaque minerals under a high power oil immersion lens showed that they consist of (a) separate grains of ilmenite, (b) intergrowths of homogeneous grains of ilmenite and magnetite and (c) grains of magnetite containing narrow or wide exsolution lamellae of ilmenite. The occurrence of magnetite grains that contain exsolved ilmenite suggests that the homogeneous grains of ilmenite found in the ilmenite-magnetite intergrowths are also of exsolution origin (Wright 1961, states that exsolution in solid solutions probably begins with separation of the fairly large ilmenite grains that are found in ilmenite-magnetite intergrowths, and as exsolution becomes more sluggish the ilmenite remains in the magnetite grains as blebs or lamellae). Polished mounts of hand-magnet concentrates from PB.48, the Pankshin syenite, and PB.51, an amphibole-biotite granite from Pankshin, were also made. The oxides present in PB.48 are the same as the oxides in the Mama gabbro; exsolved ilmenite occurring either as wide lamellae along (111) planes or as fine parallel lamellae in the host magnetite, and separate grains of ilmenite and magnetite. Some of the magnetite grains show marginal alteration to haemetite. Rare grains of rutile are also present in the concentrate. PB.51 contains considerably less ilmenite than PB.48 and the magnetite grains are generally homogeneous. Almost

every grain in this concentrate shows some degree of martitisation.

It is obvious that the rocks previously mentioned originally contained homogeneous titaniferous magnetites, that were presumably formed at high temperatures. Since the formation of these titaniferous magnetites, conditions of prolonged cooling have brought about the extensive unmixing now apparent. The commencement of unmixing may be due to either (a) oxidation of ulvöspinel, which is then exsolved as ilmenite from the original magnetite-ulvöspinel solid solution, or (b) a combination of (a) and, possibly, the inversion of γ -FeTiO₃ which may form part of the magnetite-ulvöspinel solid solution series at high temperature (Vincent et. al. 1957).

Other polished mounts examined by the author were of ilmenite concentrates from PB. 6 and PB.13, both porphyries from Liruei, PB.24 and PB.97, both amphibole-biotite granites from Sara-Pier and Jos-Bukuru respectively. There are no special features of interest about the ilmenite concentrates, which consist of homogeneous grains that are frequently fractured. Occasionally the grains contain minute inclusions of, or are marginally intergrown with, gangue minerals. In the original rocks, from which the concentrates come, thin sections show that the ilmenite grains are often associated with deep reddish alteration products that may include rutile.

Composition of the ilmenites:

Partial or complete analyses were made of the four ilmenites referred to above and these analyses are given in Table 15, together with the analyses of the ilmenites from the Skaergaard intrusion (Vincent and Phillips, 1954) for comparison.

The molecular proportions of FeO, TiO₂ and Fe₂O₃ in the Nigerian ilmenites have been recalculated to 100 and the results plotted on Fig. 18(a) which shows part of the system FeO.TiO₂.Fe₂O₃. In a similar way the Skaergaard ilmenites have also been plotted on this figure, their positions being slightly different from those given by Vincent and Phillips (1954) as the minor oxides in these ilmenites have not been taken into account by the present author. I.24, the completely analysed Nigerian ilmenite, and the Skaergaard ilmenites have also been plotted on Fig. 18(b)

TABLE 15

Analyses of ilmenite

	Nigerian ilmenite				Skaergaard ilmenite				
	I.13	I. 6	I.97	I.24	1.	2.	3.	4.	5.
FeO	37.86	43.47	43.54	39.40	39.64	40.39	42.72	43.30	42.18
MgO	n.d.	n.d.	n.d.	1.76	3.27	2.27	1.48	0.62	0.46
MnO	1.75	1.90	2.42	1.68	0.47	0.41	0.62	0.65	1.44
CaO	n.d.	n.d.	n.d.	2.78	0.37	0.34	0.48	0.46	0.71
TiO ₂	44.25	46.21	45.48	42.54	51.19	49.89	51.97	50.31	50.02
SiO ₂	0.15	nil	0.34	0.73	0.09	0.14	0.23	0.57	0.51
Fe ₂ O ₃	8.04	6.42	6.78	10.43	4.25	6.26	2.58	3.92	4.19
Al ₂ O ₃	0.14	tr.	0.20	0.37	0.17	0.02	nil	tr.	n.d.
V ₂ O ₅	n.d.	n.d.	n.d.	n.d.	0.32	0.18	nil	nil	n.d.
Cr ₂ O ₃	n.d.	n.d.	n.d.	n.d.	nil	nil	nil	nil	n.d.
H ₂ O ₂	n.d.	n.d.	n.d.	n.d.	0.03	0.06	0.04	0.07	0.13
	92.19	98.00	98.76	99.69	99.80	99.96	100.12	99.90	99.64
<u>Mol. %:</u>									
FeO	45.5	49	49	48	45	46	47	48	47
TiO ₂	49	47	46.5	46.5	52.5	51	51	50	50.5
Fe ₂ O ₃	4.5	4	4.5	5.5	2.5	3	2	2	2.5

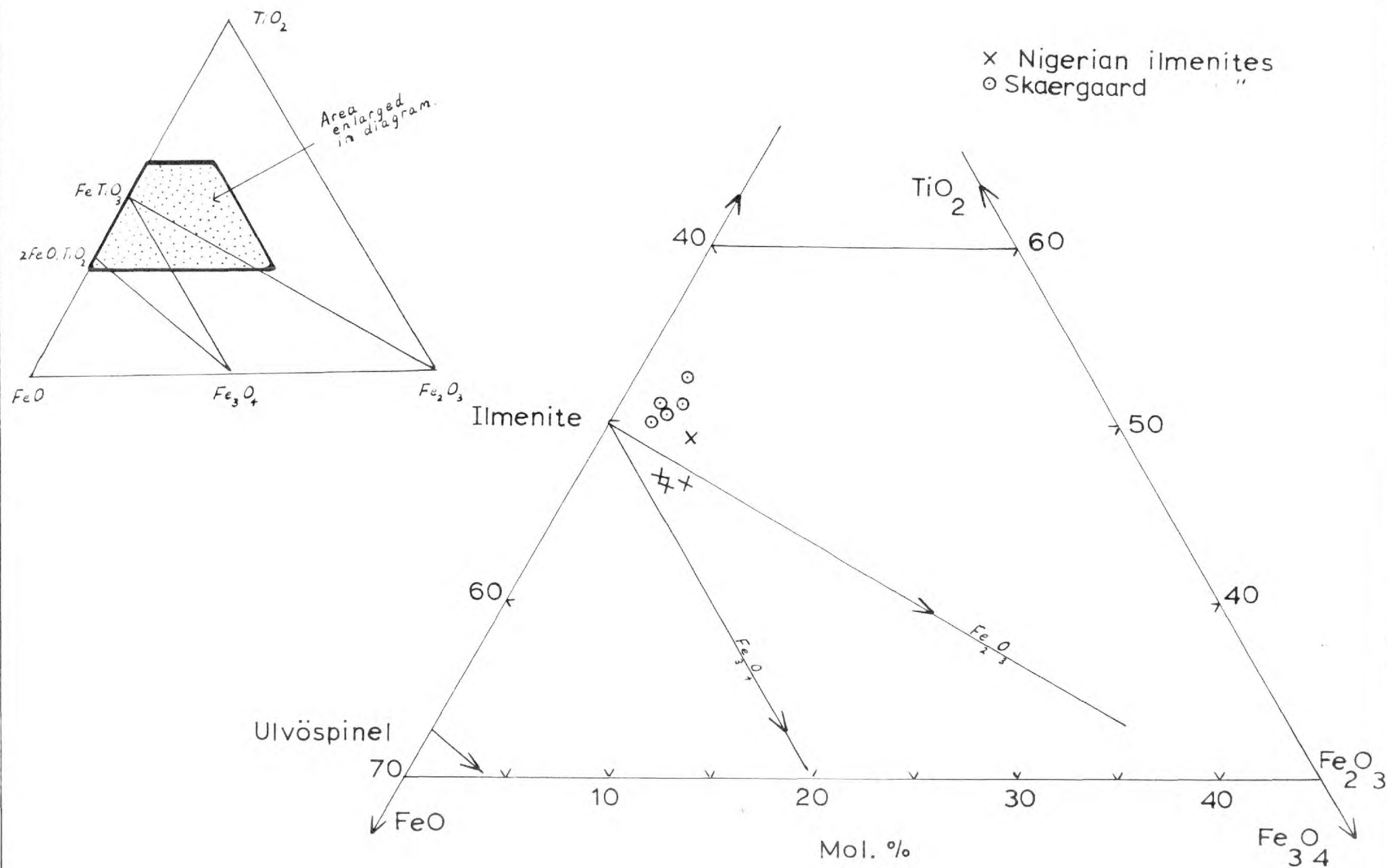
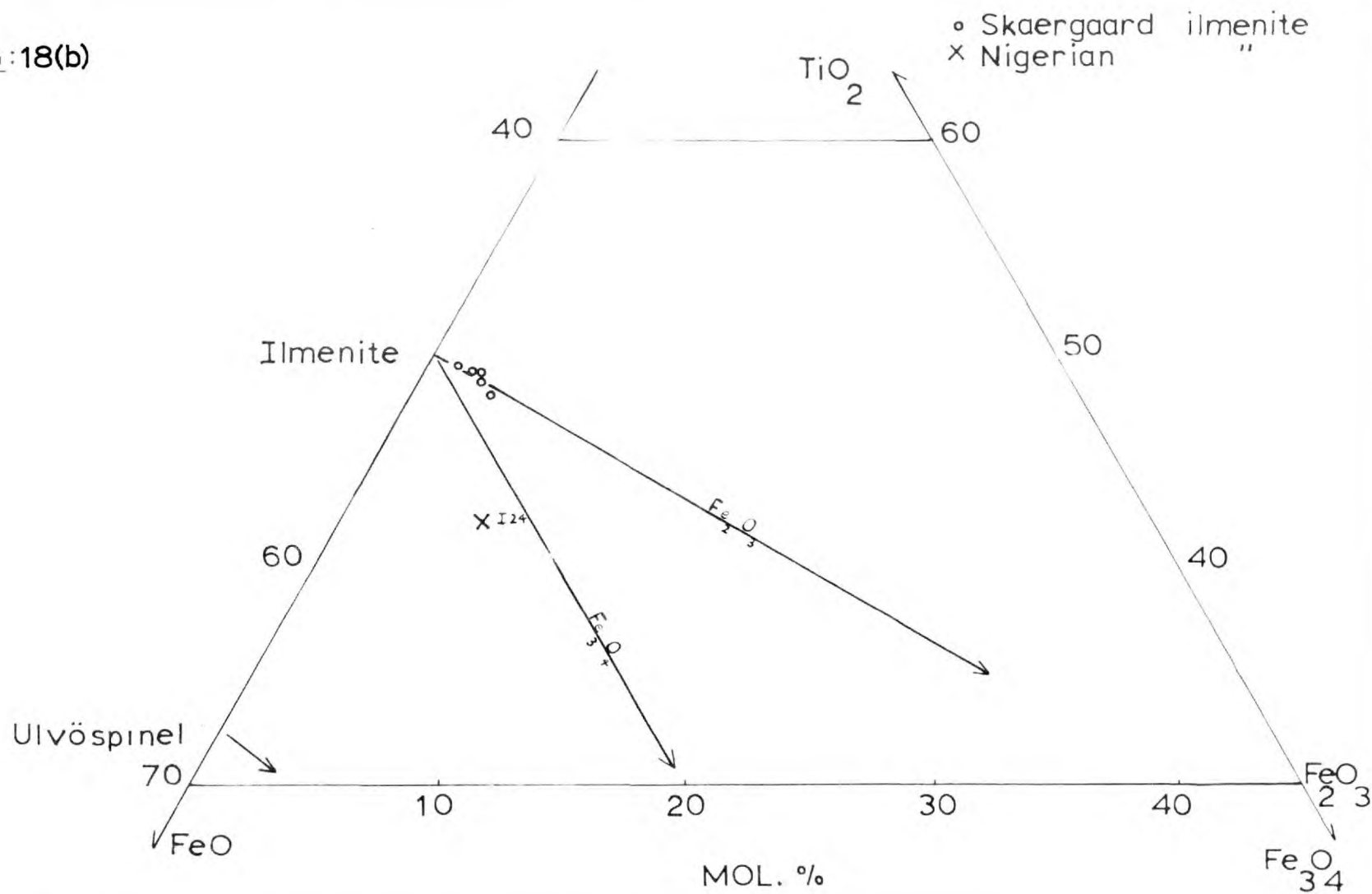


FIG:18(a) Molecular composition of Nigerian ilmenites compared with ilmenites from Skaergaard.

FIG:18(b)



which shows the same part of the system $\text{FeO} \cdot \text{TiO}_2 \cdot \text{Fe}_2\text{O}_3$ as Fig. 18(a), but in the former figure FeO includes MnO, MgO and CaO, TiO_2 includes SiO_2 , and Fe_2O_3 includes Al_2O_3 .

It is clear from an examination of the analyses and from Figs. 18(a) and (b) that the Nigerian ilmenites have an unusual composition; they are deficient in TiO_2 relative to FeO and other divalent oxides, and they contain a high percentage of ferric oxide. In contrast the Skaergaard ilmenites have ferrous oxide and titania contents that are very close to those of an ideal ilmenite, and the maximum ferric oxide content of the Skaergaard ilmenites is 6.26%. The MnO and Fe_2O_3 contents of the Nigerian ilmenites compare with those of ilmenite from Bahia, Brazil (reported by Saldanha et. al. 1958) which contain 2.00% MnO and 9.40% Fe_2O_3 . The low silica and alumina contents of the analysed ilmenites imply that they were reasonably free from gangue impurity, and it is doubtful whether very small amounts of such impurity could affect the composition of the ilmenites to any great extent. X-ray powder photographs were taken of all the ilmenites but they failed to reveal the presence of either magnetite or haemetite lines. Vickers micro-hardness tests were also carried out on two of the ilmenites (I. 6 and I.97, by Dr. A.P. Millman) and the results were compatible with those for other ilmenites, although the figures had a bias toward the magnetite rather than the haemetite side of the magnetite-ilmenite-haemetite hardness series. The cell-parameters of I.97 have been determined from an X-ray powder photograph (Co.K α radiation, 9cm aperture, 17 hours exposure), and the photograph gave a ca. 5.09Å and c ca. 14.09Å. I.97 has a molecular content of ferric iron of nearly 7% and according to the curves of Basta (1953) (given by Vincent et. al. 1957) the cell-parameters should be a ca. 5.08Å and c ca. 14.02Å. It seems most probable that the large sizes of the parameters of I.97 are due to the high content of MnO (2.4%) and to the fact that it probably contains some MgO and CaO. Vincent et. al. (1957) and others have pointed out that MgTiO_3 and MnTiO_3 , in particular, have larger cell dimensions than ilmenite.

Among possible explanations of the high ferric iron and low titania contents of the analysed ilmenites are (a) they have undergone some alteration, e.g. to rutile, which has reduced the original titania contents,

whilst at the same time some of the ferrous iron has been oxidised to ferric and (b) they contain magnetite or haemetite in solid solution. As mentioned above, many of the ilmenite grains, in ordinary thin section, are associated with alteration products and some oxidation of ferrous to ferric iron seems possible; Wilkinson (1957) has pointed out that the unmixing process in iron-titanium oxide solid solutions is probably complicated by oxidation-reduction reactions. With regard to (b), Vincent et. al. (1957) have suggested that any titanomagnetite solid solution which crystallises with a composition near the Fe_3O_4 - FeTiO_3 binary series is likely to exsolve an FeTiO_3 - Fe_2O_3 solid solution. On cooling, this ferri-ilmenite phase would change in composition until it approaches FeTiO_3 . Such an origin could be postulated for the Nigerian ilmenites, but it would have to be assumed that either cooling of the parent rocks has not continued long enough for the composition of the ferri-ilmenites to approach FeTiO_3 , or the parent rocks were cooled suddenly. (The latter could be applied to the porphyries PB. 6 and PB.13, both of which have fine-grained groundmasses). The main problem with the Nigerian ilmenites is, however, that they contain excess $\text{FeO}.\text{Fe}_2\text{O}_3$; Stumpfl (1961) has described ilmenites from Assynt rocks that contain exsolution lamellae of magnetite and this author has concluded that the ilmenites contained an original excess of FeO and Fe_2O_3 . Polished sections of the Nigerian ilmenites failed to reveal any exsolution lamellae of magnetite, but Dr. Stumpfl (private communication) does not think that the lack of exsolution lamellae is particularly significant; he points out that both FeO and Fe_2O_3 may be kept in solid solution even at low temperatures, and he also points out that Edwards (1954) considers that at least 6% Fe_2O_3 would need to be present (and possibly more) in ilmenite before unmixing could start. Further work on the composition of iron-titanium oxides from the Nigerian granites is obviously desirable, and such work may help provide a satisfactory explanation as to why there is a general excess of divalent oxides in the analysed ilmenites.

As three of the ilmenite analyses are incomplete it is not possible to discuss composition trends, but there is a slight increase in titania with decreasing molecular percentage of ferrous iron.

SECTION C

COMPOSITIONAL TRENDS IN ANALYSED MINERALS:

(a) Factors that affect the composition of individual minerals:

In discussing the compositional trends in the analysed minerals the author is assuming that as differentiation proceeds in a magma, the ferromagnesian minerals produced in successively younger fractions will become depleted in magnesia and enriched in iron. Ferromagnesian minerals such as amphiboles may also become depleted in lime and alumina and enriched in alkalis and silica.

In this connexion the $(\text{Fe}'' + \text{Mn})100:\text{Fe}'' + \text{Mn} + \text{Mg}$ ratios of a group of ferromagnesian minerals such as the amphiboles, can be used to indicate the relative positions of the parent rocks in a series of genetically related rocks, the lowest ratios usually being found in the minerals from early differentiates. Reference back to Table 7b will show, however, that the ferrohastingsite from a presumably early differentiate such as the Pankshin syenite (PB.48) is apparently more enriched in iron than A.51, the ferrohastingsite from an intrusion of amphibole-biotite granite (PB.51) occurring to the north of the Pankshin syenite. Possible reasons for such a situation are (i) the syenite may be genetically unrelated to the granite intrusions, or it may belong to a magmatic cycle of activity that is later than that to which the amphibole-biotite granite belongs, (ii) the amphibole-biotite granite has been contaminated by basic material, and (iii) the amphibole-biotite granite may contain a higher proportion of early formed magnetite than the syenite, and removal of ferrous iron to form the magnetite in the granite would have increased the magnesia content of the amphibole A.51. In regard to (i) it seems fairly certain that the syenite is an early intrusion, older than and genetically related to the granites in the immediate area (Turner, 1961); but if this is so it is plain that a bare comparison of the $(\text{Fe}'' + \text{Mn})100:\text{Fe}'' + \text{Mn} + \text{Mg}$ ratio for the amphibole from this syenite with the ratios for the amphiboles from the granites, would give a misleading idea of the time relationships of these amphiboles in a differentiated sequence. The possibility of there having been some contamination of PB.51 cannot be ruled out, for the area in which this granite occurs is one in which there

has been considerable mixing of basic and acid magmas to give hybrid rocks that have since been partly metasomatised and veined by a later granite intrusion (Turner, 1961), from which A.51 comes. With respect to (iii) there is not a great deal of difference in the percentage of iron-titanium oxides present in PB.51 and PB.48, but examination of the concentrates of the latter minerals from the two rocks showed that a higher proportion of magnetite was present in PB.51 than in PB.48; this suggests that the formation of magnetite in PB.51 could have affected the iron:magnesia ratio of the amphibole A.51.

Apart from the possibility that contamination may have affected the composition of any of the minerals being discussed, it is also obvious that before using ratios of any kind in order to trace changes in composition with time in particular mineral groups, it is necessary to take into account the number and nature of the co-existing minerals in the rocks concerned, and the possible distribution of cations among the minerals. These factors are probably of particular importance in minerals such as the amphiboles, which may be of late formation in rocks containing fayalite, pyroxene and iron-oxides and which tend to be repositories for small amounts of a large number of cations.

DeVore (1957) discussed the general distribution of cations in pyroxenes, amphiboles and biotites, and their distribution between co-existing pairs of minerals: ortho- and calcium-rich pyroxenes, calcium-rich pyroxene-hornblende, and hornblende-biotite. He showed that in co-existing calcium-rich pyroxene-hornblende pairs, the hornblende usually has higher Al^{vi} , Al^{iv} , Fe''' , Ti and Na contents than the pyroxene, and in co-existing hornblende-biotite pairs the hornblende has higher Na and Al^{vi} and lower Fe''' , Ti and Al^{iv} contents than the biotite.

Data for two pairs of co-existing minerals (similar in type to those discussed by DeVore) from Nigerian rocks are given below: Px.48/A.48, a ferroaugite-ferrohastingsite pair from the Pankshin syenite, and A.51/B.51, a ferrohastingsite-biotite pair from an amphibole-biotite granite.

Distribution of cations

	Calculated to 24000 (O + OH + F)		Calculated on basis of 23000 oxygens	
	<u>Px.48</u>	<u>A.48</u>	<u>B.51</u>	<u>A.51</u>
Al ^{iv}	364	1570	2080	1591
Al ^{vi}	-	100	193	-
Fe ^{'''}	400	600	620	513
Ti	88	270	413	220
Na	276	720	134	597

From this data it is clear that the distribution of cations in these co-existing minerals is in general agreement with the findings of DeVore, although ferrohastingsite A.51 does not contain any Al^{vi}.

Data for three other pairs of co-existing minerals, of types that differ slightly from those mentioned previously, are also available: B.29/R.30, a biotite-alkali amphibole pair from a riebeckite granite; Ag.20/R.20 and Ag.92/R.92, both aegirine-alkali amphibole pairs from aegirine-riebeckite granites.

Distribution of cations - calculated to 24000 (O + OH + F)

	<u>B.29</u>	<u>R.30</u>	<u>Ag.20</u>	<u>R.20</u>	<u>Ag.92</u>	<u>R.92</u>
Al ^{iv}	1274	110	84	120	108	4
Al ^{vi}	-	-	-	-	-	-
Fe ^{'''(vi)}	-	1320	3496	1410	3872	1500
Ti	362	-	44	-	24	-
Na	240	2720	3784	2050	4092	2620

The distribution of cations between B.29 and R.30 is slightly different from that between B.51 and A.51, in particular the ferric iron content of R.30 is very high compared with B.29 which has ferric iron present in tetrahedral sites only; it should be pointed out that B.29 and R.30 come from the biotite-rich and alkali-amphibole-rich facies' respectively, of the parent rock, and are not as closely comparable as B.51 and A.51. In both the aegirine-alkali-amphibole pairs, the aegirine has higher Ti, Fe^{'''} and Na contents than the amphibole.

Returning to the problem of iron enrichment in co-existing minerals, DeVore found that on the basis of the Mg x 100:Mg + Fe^{''} ratios, the calcium-rich pyroxenes were enriched in magnesia and the biotites

were generally enriched in iron relative to co-existing amphiboles. DeVore also pointed out that the simple $Mg \times 100 : Mg + Fe^{''}$ ratios might be complicated by the distribution of Al^{vi} , Ti and $Fe^{''}$ between 8 and 6 co-ordinated positions; part of the total Al^{vi} , Ti and $Fe^{''}$ could be occupying vacant 8 co-ordinated sites and the remainder would be occupying normal 6 co-ordinated sites. It was then assumed by DeVore that $Fe^{''}$ would not be found in 6 co-ordinated sites having anions in common with similar sites occupied by Al^{vi} , Ti or $Fe^{''}$; such sites would be open to Mg ions only and the mineral enriched in Mg as a result. Following from this assumption DeVore deducted from the total Mg contents the amount of Mg present in influenced 6 co-ordinated positions in each mineral, and the remaining Mg was used in recalculating the $Mg \times 100 : Fe^{''} + Mg$ ratios.

The author has calculated the normal $Mg \times 100 : Mg + Fe^{''}$ ratios for the co-existing pairs Px.48/A.48 and B.51/A.51, and recalculated the ratios using the method given by DeVore:

	<u>Px.48</u>	<u>A.48</u>	<u>B.51</u>	<u>A.51</u>
Mg	1124	590	1559	1331
Fe ^{''}	2774	3500	3293	2915
Mg x 100:Mg + Fe ^{''}				
Normal	29	14	32	31
Recalculated (1)	2	0	0	3
(2)	13	0	0	14

On comparing the recalculated ratios for A.48 and A.51 it appears that A.51 is slightly more enriched in iron than A.48, but the author is uncertain as to whether such a comparison is justifiable.

The main points to emerge from the preceding discussion are:

- (a) the composition and $(Fe^{''} + Mn)100 : Fe^{''} + Mn + Mg$ ratios of amphiboles occurring with fayalite-pyroxene assemblages have been largely determined by the composition of the latter minerals, and not directly by the bulk composition of the parent rocks. This suggests that a comparison of iron-magnesia ratios can only be made among amphiboles from similar rock types;
- (b) when comparing degrees of soda enrichment in amphiboles, the amount and composition of co-existing aegirine must be taken into

account, for the formation of the latter may reduce the amount of soda and ferric iron available to the amphibole, or considerably reduce the amount of alkali amphibole that can form. Where possible it would again seem better to make comparisons of composition among alkali amphiboles from similar rocks; (c) the formation of biotite in any significant amount probably reduces the amount of alumina available to the amphibole; (d) it is also possible that, as suggested previously, a high percentage of early-formed magnetite in the parent rock may affect the iron:magnesia ratio of any amphibole that forms.

(b) Chemical trends in the analysed ferromagnesian minerals:

Having considered a few of the factors that may affect the composition of any particular ferromagnesian mineral, it is now possible to compare minerals from similar assemblages in order to discover whether there have been any major changes in mineral composition that could be correlated with changes in the nature of the parent magma.

In Fig. 19 the molecular proportions of the major oxides present in all the analysed ferromagnesian minerals have been plotted, and the compositional trends that will now be discussed are clearly illustrated.

Of the analysed ferrohastingsites, A.38, A.47 and A.71 are from amphibole-fayalite granites that contain small amounts of biotite and traces of pyroxene in addition to fayalite. Table 16 shows that there is progressive iron enrichment in the minerals but that the Ca:Ca + alkali ratio hardly changes. Of the ferrohastingsites from amphibole-biotite granites, A.51 is relatively enriched in magnesia as has already been noted, but A.45, A.96 and A.97 show a considerable and increasing degree of iron enrichment. There is also a very slight decrease in the ratio Ca:Ca + alkali in these ferrohastingsites. Iron enrichment in the analysed calcium-rich amphiboles reaches a maximum of 98.5 in A.13, the intermediate amphibole, and the Ca:Ca + alkali ratio has decreased to 35. This amphibole is associated with fayalite and a possible sodic-ferrohedenbergite, and the mineral with which it can perhaps be compared is A.37, the calcium-rich arfvedsonite from the Hotum arfvedsonite granite which contains fayalite and pyroxene relics. Both A.13 and A.37 are low

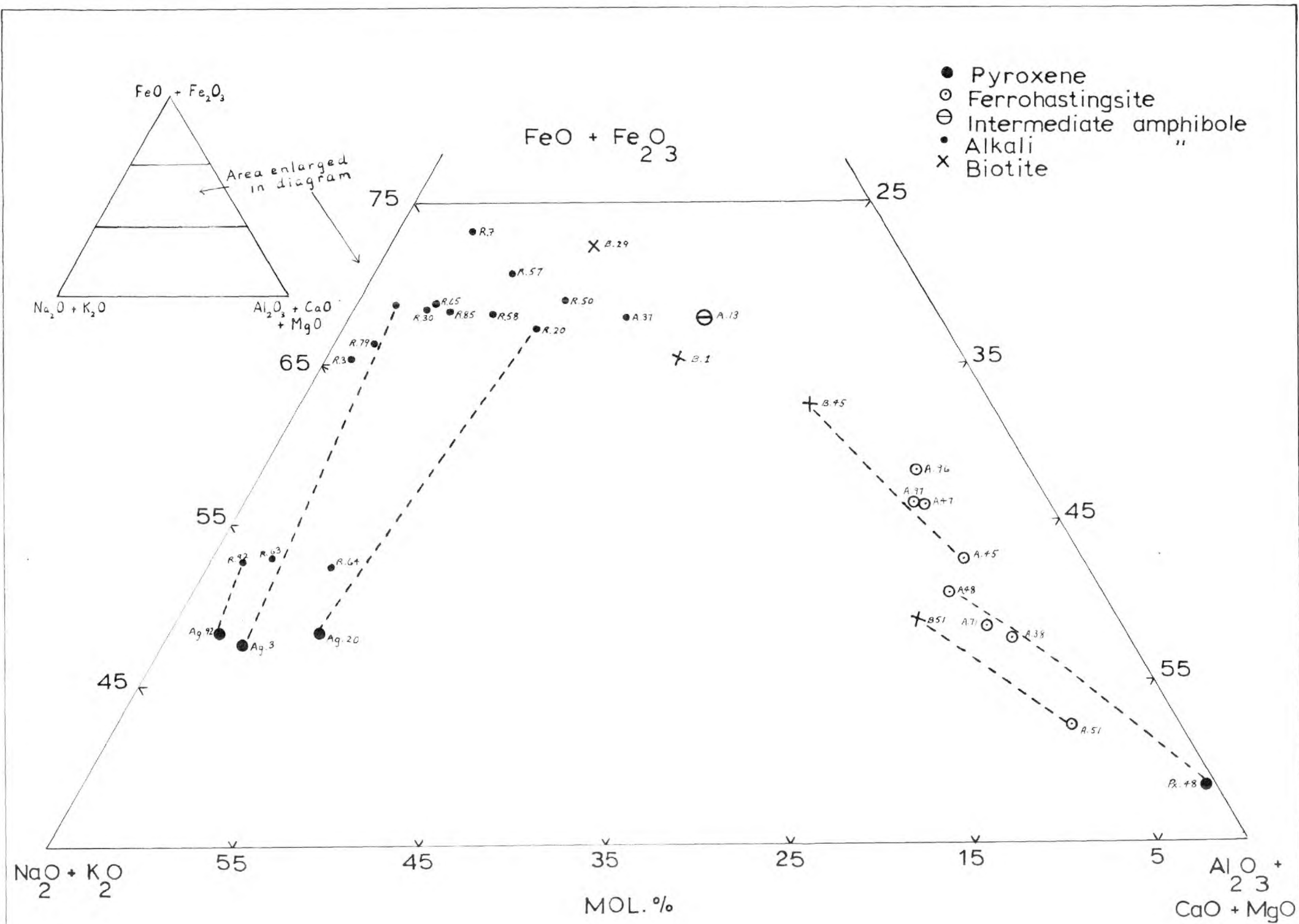


FIG: 19 Major compositional trends in analysed ferromagnesian minerals. Tie lines join co-existing minerals.

<u>TABLE 16</u> Iron:magnesia and calcium:alkali ratios of amphiboles and biotites					
		$\frac{(\text{Fe}^{++} + \text{Mn}) \times 100}{\text{Fe}^{++} + \text{Mn} + \text{Mg}}$		$\frac{\text{Ca}}{\text{Ca} + \text{Alkali}}$	
Rock type	Sample	Amphibole	Biotite	Ca-amphibole	Alkali amphibole
Syenite	PB.48	85.9	-	62	-
Amphibole-fayalite granites	PB.38	78.3	-	65	-
	PB.47	88.6	-	65	-
	PB.71	89.5	-	65	-
Amphibole-pyroxene-fayalite granite and porphyry	PB.13	98	-	35	-
	PB.37	98	-	-	25
Amphibole-biotite granites	PB.51	69.5	69	69	-
	PB.45	88.6	87	64	-
	PB.96	93.7	-	64	-
	PB.97	95.7	-	61	-
Biotite granite	B. 1	-	98		
Riebeckite-biotite granite	PB.29	-	98		
Riebeckite-granites (+ aegirine, biotite or astrophyllite)	PB.20**			-	17
	PB.50*			-	14
	PB.57*			-	11
	PB.58*			-	10.5
	PB.64			-	11
	PB.65			-	6
	PB. 7**			-	5
Albite-riebeckite granites (+ aegirine or biotite)	PB.30			-	5
	PB.63			-	5
	PB.85			-	4
	PB.92			-	2.5
	PB.79			-	2
	PB. 3			-	1

** Aegirine-rich and aegirine-poor facies respectively of same rock.

* Different facies of same rock.

in alumina compared with the ferrohastingsites, and the Ca:Ca + alkali ratio of A.37 is only 25.

The alkali amphiboles can be broadly divided into two types: (a) those that come from riebeckite granites in which there may be traces of biotite or astrophyllite, and in which the percentage of aegirine varies from a trace to 1%; (b) alkali amphiboles from albite-riebeckite granites which may contain abundant aegirine. As the normal iron:magnesia ratio is no longer of importance, the author has used the Ca:Ca + alkali ratio as an indication of a compositional trend in the alkali amphiboles.

In the amphiboles of type (a) there is a decrease in the Ca:Ca + alkali ratio from 17 in R.20 to 5 in R.30, and in amphiboles of type (b) the ratio decreases from 5 in R.63 to 1 in R.3. It is obvious that amphiboles from the albite-riebeckite granites have low or very low Ca:Ca + alkali ratios, regardless of whether or not they co-exist with aegirine, (Table 16). Alumina is very low in all the alkali amphiboles but tends to be slightly higher in those of type (a). There is a gradual increase in substitution of Li for Fe⁺⁺ and enrichment in Li is at a maximum in several of the amphiboles from the albite-riebeckite granites. Two of the alkali amphiboles are of particular interest, R.20 and R. 7 from an aegirine-rich and aegirine-poor facies respectively of the parent rock; the two minerals differ considerably in composition and it is possible that the parent rock is a composite intrusion.

The degree of alkali enrichment shown by the two aegirines, Ag. 20 and Ag.92, parallels that shown by the co-existing alkali amphiboles, and it is of interest to note that the co-existing pyroxene and amphibole from PB.92 have the maximum possible contents of alkali.

The few analyses of biotite suggest that they follow the same general pattern of enrichment in iron and alkalis. Biotites B.51 and B.45 have (Fe⁺⁺ + Mn)100:Fe⁺⁺ + Mn + Mg ratios that are similar to those of the co-existing ferrohastingsites (see Table 16). Iron enrichment in biotites from biotite granites appears to be at a maximum in a ferruginous biotite from Liruei (Table 13), the analysis of which was given by Jacobson et. al. (1958), but the alumina content of this biotite is normal. B.29, discussed by the author in the section on biotites, is also a ferruginous

biotite that shows extreme iron enrichment but the potash content is slightly higher and the alumina content considerably lower than that of the biotite from Liruei.

CHEMISTRY OF THE PLUTONIC ROCKS OF THE YOUNGER GRANITE COMPLEXES:

The following summary of the salient features of the chemistry of the plutonic members of the Younger Granites is based on the work of Jacobson et. al. (1958), Turner (1961), Bowden (1961) and the author. A more detailed discussion of the chemistry of some of the granites will be found in later sections of the thesis that deal with individual complexes.

Gabbros and syenites:

The small number of analyses of gabbro that are available show the composition of these basic rocks to be quite normal, and they are characterised by high normative an, di, ol, mt, and il. Syenites and quartz-syenites occur in the complexes and it is possible that some of these intermediate rocks are of hybrid type (see Turner 1961). However, the analyses of the syenites do compare with many of those of syenites from the Kungnat Fjeld alkaline complex, Greenland, which have a silica content between 56% and 64% (Upton, 1960). The alumina content of the Nigerian syenites varies, but the quartz-syenites tend to have a slightly higher percentage of normative anorthite. Normative di, hy, il and mt are moderately high in the syenites.

Amphibole granites:

(a) Amphibole-fayalite, quartz-fayalite-pyroxene, and arfvedsonite-fayalite granites and porphyries:

These granites, which include the early ring intrusions of amphibole-fayalite granite that Black (1958) considered to represent the parent magma of the Nigerian granites, show considerable variation in composition. They may have a moderately large molecular excess of alumina over alkalis, indicated by high normative an; a slight molecular excess of alumina over alkalis, indicated by low normative an; or a molecular excess of alkalis over alumina, indicated by low or moderately high normative ac. Normative il and mt are, of course, much lower than in the basic and intermediate rocks and rarely amount to more than 2% together.

(b) Amphibole-biotite granites:

The amphibole-biotite granites fall within the compositional field of the other amphibole granites, but available analyses show that they always have an excess of alumina over alkalis and contain normative an.

Biotite granites:

The majority of biotite granites have a higher ratio of alumina:alkalis (molecular ratio) than the other Nigerian granites, nevertheless their compositional field slightly overlaps that of the amphibole granites. Generally the biotite granites contain normative an, and the albite-biotite granites commonly contain normative C; more rarely the albite-biotite granites contain normative ac, e.g. albite-biotite granite from Sara-Fier complex.

Riebeckite granites:

The riebeckite granites constitute a chemically more homogeneous group than those considered above. They are all high in molecular content of alkalis relative to alumina and they contain normative ac, whilst the albite-riebeckite granites contain normative ns. The silica content of the albite-riebeckite granites is much lower than in other riebeckite granites (71% against 75%) and they are also rich in fluorine. The lime, magnesia and total iron contents of all the riebeckite granites are low, and there may be little or no normative di, hy, il, or mt.

The great differences in the normative composition of the biotite and riebeckite granites led Jacobson et. al. (1958) to suggest that differentiation in the Nigerian granites proceeded along two divergent trends; an alumina-rich trend resulting in formation of biotite granites, and an alkali-rich trend resulting in the formation of riebeckite granites.

TRENDS IN THE PLUTONIC ROCKS OF THE YOUNGER GRANITE COMPLEXES:

Before any attempt is made to distinguish the main compositional trends in the intrusive rocks from the Younger Granite complexes it is necessary to consider the various factors that may have affected the original bulk composition of many of the rocks.

1. Thin sections of the Mama biotite gabbro, from the Tof complex, which is considered to be typical of the gabbros occurring in the complexes,

show that there has been considerable post-crystallisation alteration of the rock. The felspar is frequently nearly completely sericitised; part of the biotite appears to have undergone an early recrystallisation into sheaves of small grains, and most of the biotite, including the recrystallised material, has been partly or wholly altered to chlorite; pyroxene has been partly converted to uranalite which in turn has been altered to chlorite. Epidote and calcite are other common secondary alteration products present in this gabbro.

2. In the amphibole-fayalite and pyroxene-fayalite granites and porphyries, the fayalite is generally altered to serpentine or other minerals including, possibly, iron-oxide which is associated with the alteration products, and fresh fayalite is rare. Pyroxene appears to have suffered some loss of iron, as brownish limonitic oxide is often present in the pyroxene. The original iron-titanium minerals of these rocks may also be associated with undoubted alteration products that apparently include rutile.

3. The biotite in hornblende-biotite granites has often been subject to hydrothermal alteration and, on analytical evidence, loss of potash and secondary oxidation of ferrous to ferric iron are the most obvious results of such alteration. In the Fier river area of the Sara-Fier complex there has been considerable hydrothermal and metasomatic alteration of acid, basic and hybrid rocks (Turner, 1961), and in addition to the alteration of biotite mentioned above, there has been pronounced martitisation of the iron-titanium oxides in the rocks from this area, e.g. in PB.51.

4. A number of the biotite granites have been affected by the intense mineralisation that was centred around the complexes of the Jos Plateau area, particularly the biotite granites of the Jos-Bukuru complex where alluvial tin mining is concentrated. In the mineralised areas there has been some greisenisation of the upper levels of the stock-like intrusions of biotite granite. The albite-riebeckite granites from the Kigom Hills in the Jos Plateau have also been subject to late mineralisation, and fractures and cavities in these rocks have been filled with ore minerals which are accompanied by calcite.

5. Many of the amphibole granites and porphyries are xenolithic and contain variable sized fragments of earlier volcanic, or intrusive,

acid and basic rocks. PB.37 and PB.38, both from Sha-Kaleri complex, are xenolithic rocks.

6. A high proportion of the granitic rocks contain minor amounts of albite that appears to have replaced perthitic alkali feldspar and, occasionally, the ferromagnesian minerals, and in the albite-riebeckite and albite-biotite granites such secondary albite may be extensively developed. A small number of the albite-riebeckite granites, e.g. PB.79 from Amo and PB. 3 from Liruei complex, appear to have been auto-metasomatised by their own alkali-rich residual liquids that failed to escape to form pegmatites. The pegmatoidal affinities of these granites are emphasised by the accessory minerals they contain; pyrochlore, topaz and cryolite.

There is little doubt that the results of alteration by highly aqueous hydrothermal solutions (evidenced by the alteration of biotites to hydrous biotites), mineralising solutions rich in metals (shown by the late deposition of ore minerals in fractures and cavities, e.g. in the albite-riebeckite granites of Kigom Hills), and strongly alkaline residual magmatic fractions (as evidenced by the albitisation of certain granites), have been to modify the original bulk compositions of many of the intrusive rocks present in the complexes. Such modifications to original composition may not have been great enough to diminish appreciably the large chemical differences between the basic and intermediate rocks and the granites; but in the granites which have a rather narrow range of composition comparatively small losses or additions of material may have served to obscure or emphasise the original chemical differences between the various rock types. In particular there appears to have been a considerable addition of soda and alumina to, and loss of silica from, the albite-riebeckite granites and a smaller addition of soda and alumina to the albite-biotite granites. The following analyses seem to support the suggestion that the albite-riebeckite granites in particular are not normal products of differentiation, as they bear very little resemblance, chemically, to (a) the average analysis of 35 comendites, paisanites and peralkaline granophyres, as given by Carmichael (1962), (b) the average analysis of 40 pantellerites, given by the same author, and

(c) the analysis of comenditic rhyolite from Liruei complex, Nigeria, or (d) the analysis of a rhyolite with a slight molecular excess of alkali, from Buji complex, Nigeria.

	<u>Normative composition</u>				
	<u>(a)</u>	<u>(b)</u>	<u>(c)</u>	<u>(d)</u>	<u>(e)</u>
Qtz	30.7	27.8	30.5	32.3	20.5
Or	27.8	25.6	28.1	31.9	25.3
Ab	32.0	25.2	29.7	32.5	42.2
Ac	4.6	11.1	6.0	0.4	5.2
Ns	-	1.8	0.3	-	1.8
Wo	0.9	1.3	-	-	-
En	0.4	0.5	-	-	-
Fs	1.8	5.8	-	-	-
Di	-	-	0.8	-	-
Hy	-	-	2.4	0.5	2.5
Mt	1.2	-	-	0.8	-
Il	0.6	0.9	0.3	0.3	-

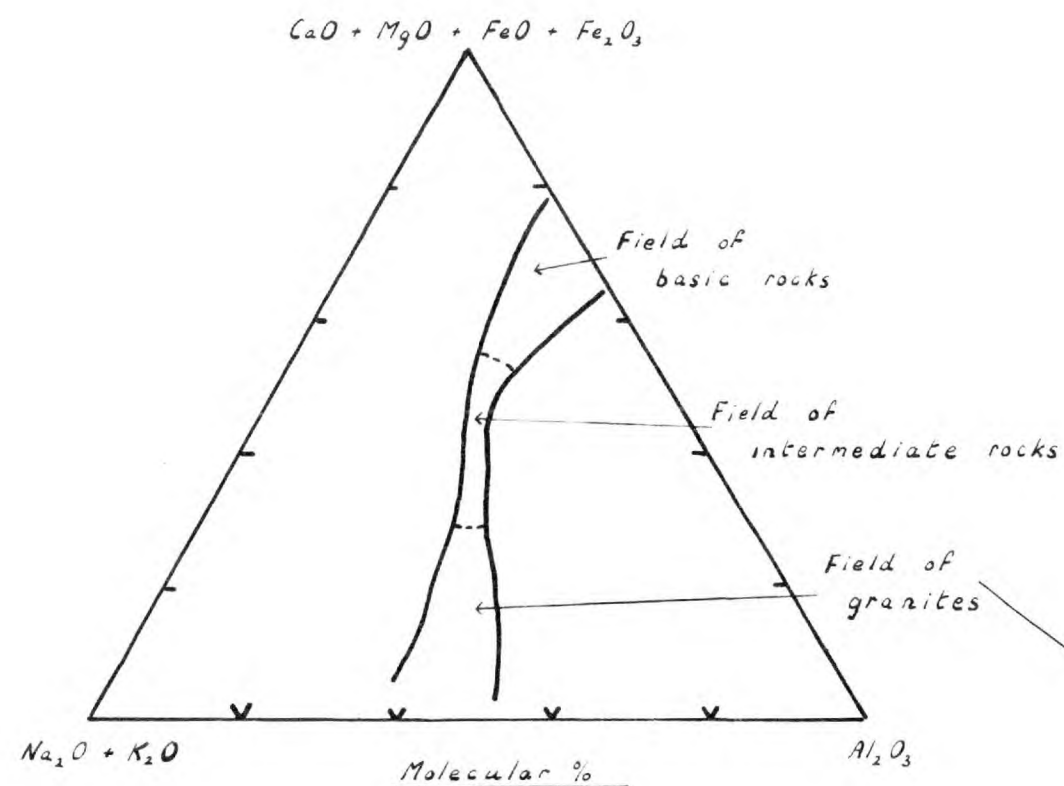
(a), (b), (c) and (d) are as mentioned above and (e) is the average of two analyses of albite-riebeckite granite from Nigeria. The very low quartz and high albite contents of the albite-riebeckite granites from Nigeria distinguish them from all the other analyses quoted above, and it is obvious that these albite-riebeckite granites have compositions that differ greatly from those of possible liquids. In view of this latter fact the author suggests that the more normal riebeckite and, possibly, biotite granites should be considered as the end products of any differentiation process that operated in the parent magma.

Major trends:

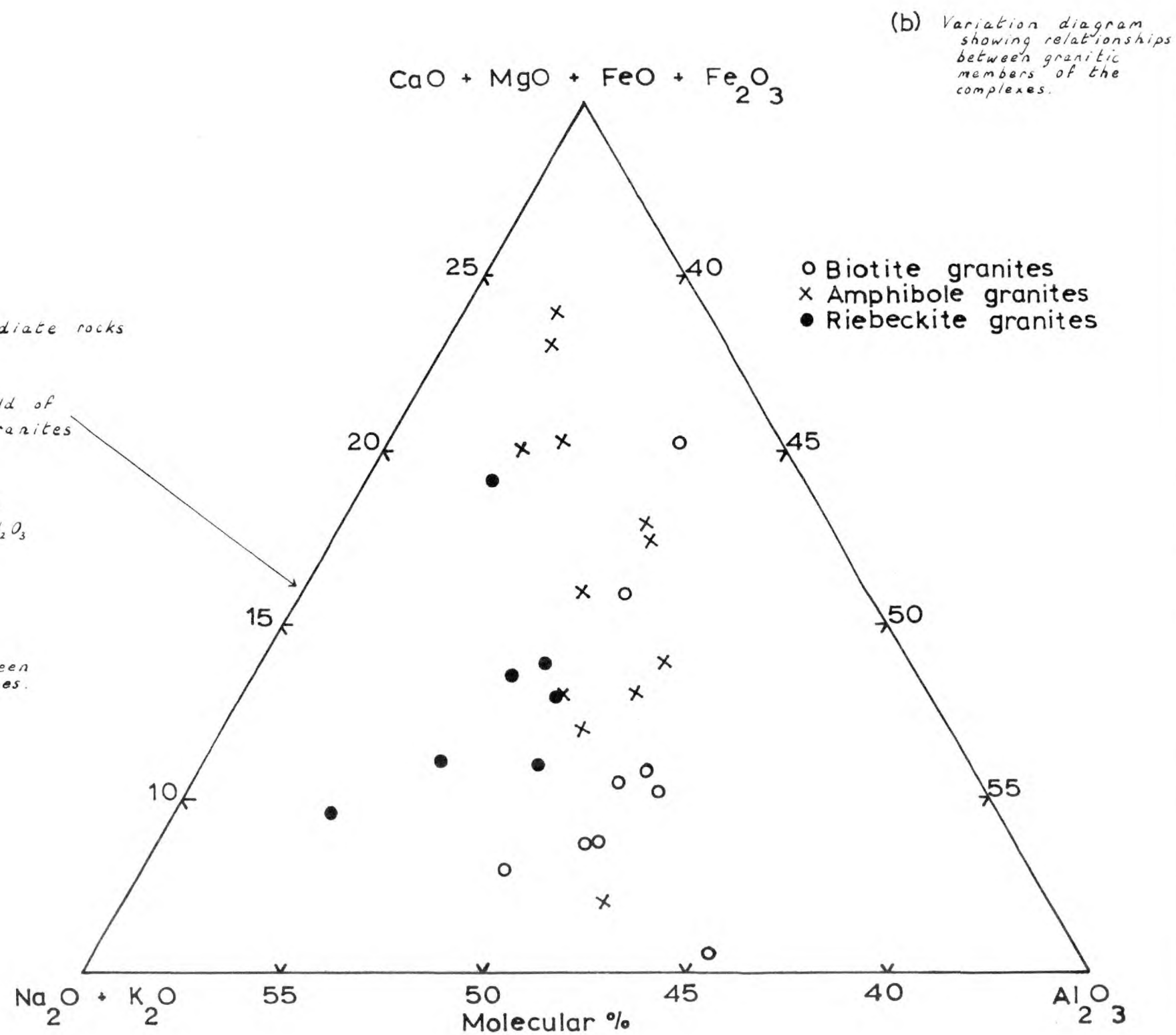
Considering all the factors mentioned above, the main trends in the plutonic rocks appear to be:

(a) Large decreases in lime, magnesia and total iron; a large increase in alkalis and a small increase in alumina, on proceeding from basic to intermediate and granitic rocks. These trends are shown in Fig.20(a), a triangular variation diagram showing changes in molecular percentages of the major oxides present in the plutonic rocks. The diagram is after

FIG. 20



(a) Variation diagram showing relationships between plutonic rocks in Younger Granite complexes. (After Jacobson et. al. 1958).



(b) Variation diagram showing relationships between granitic members of the complexes.

Jacobson et. al. (1958), supplemented by additional information from Turner (1961).

(b) In the granitic rocks there is a continuation of the trends in (a) but the degree of variation is slight and it will be seen from Fig. 20(b) that the fields of composition of the main granite types show some overlap.

Although there is a considerable increase in the molecular percentage of alkalis, relative to the other major oxides, in the late intrusions in the Nigerian complexes, it is of interest to note that the Younger Granite Province is not highly alkaline in character and there are no alkaline rocks (in the sense used by Tilley, 1957) developed in the Province. The apparently alkaline nature of the Province is due to the unusual predominance of alkali-rich ferromagnesian minerals in the late granite intrusions.

The trends in the rocks differ slightly from the trends in the minerals, discussed previously, in which, as differentiation advanced (a) total iron first increased relative to lime, magnesia and alumina, and (b) when iron enrichment was at a maximum the minerals became enriched in alkalis relative to the other constituents.

MINOR ELEMENT DISTRIBUTION IN THE PLUTONIC ROCKS:

The distribution of minor elements Rb, Li, Ga, La, Yb, Y, Zr, Nb, Sr, Ba, Sn, Pb and F, has been discussed by Bowden (1961) and the distribution of Rb in the granites has been more fully discussed by Butler et. al. (1962). Many of the trace elements mentioned above and others, including U and Th (Jacobson et. al. 1958), reach a moderate or high level of concentration in particular types of granite and this is shown by the variety of accessory minerals in biotite or albite-biotite granites, and topaz, beryl and wolfram are associated with greisens and quartz veins in the biotite granites. The extensive alluvial concentrates of tin that occur in the Jos Plateau area are also associated with the biotite granites. Molybdenite, chalcopyrite and pyrite occur in the albite-riebeckite granites of the Kigom Hills and cryolite, pyrochlore and topaz are present in the albite-riebeckite granites from the Amo and Liruei complexes. Fluorite and zircon are common accessories in

many of the granites. A number of these minerals, e.g. fluorite, zircon, topaz and pyrochlore, appear to be of primary origin, but others, including the sulphides, are associated with the post-magmatic mineralisation that has particularly affected the granites of the Jos Plateau area.

Colorimetric determinations of trace elements Ni, Co, Pb, Cu and Zn, have been made by the author for a number of granites and the results (in ppm) are summarised below:

	<u>Ni</u>	<u>Co</u>	<u>Pb</u>	<u>Cu</u>	<u>Zn</u>
Average for 10 amphibole-fayalite granites	2	-	28	5½	29
Average for 7 amphibole-biotite granites	1½	1	11	4	148
Range for 17 riebeckite granites	0.05-14	0.05-9	12-134	3-920	100-2800

The above data for these elements can be compared with data given by Carmichael and McDonald (1961) for other acid rocks:

	<u>Ni</u>	<u>Co</u>	<u>Pb</u>	<u>Cu</u>	<u>Zn</u>
Average for Icelandic pitchstones	0.7	1.3	9	9	125
" " Arran pitchstones	1.1	1.4	18	5	52
" " Eigg pitchstones	1.2	1.3	21	5½	122
Skaergaard acid granophyre	28	6.1	< 10	136	-
70 granitic rocks (Wedepohl, 1953)	-	-	-	-	45
{ 20 granites and rhyolites, average	-	-	19	16	-
{ 20 granitic rocks, average	8	50	-	-	-

*Sandell and Goldich (1943)

It is clear from these figures that the concentration of Ni, Co, Cu, Pb and Zn in the amphibole-fayalite and amphibole-biotite granites from Nigeria are similar to the concentration of these elements in the pitchstones from the North Atlantic Tertiary Province. In the riebeckite granites there is a wide range in the concentration of all five trace elements, and the maximum contents of Pb, Cu and Zn in these granites is far higher than in any of the other acid rocks mentioned above, including those discussed by Carmichael and McDonald.

CONDITIONS OF FORMATION OF SOME FERROMAGNESIAN MINERALS IN THE
YOUNGER GRANITES:

Over a number of years various synthetic systems have been investigated (many of them in the Geophysical Laboratory, Washington) with a view to elucidating the stability relations of some of the more common ferromagnesian minerals.

Experimental work that is of particular relevance to problems of formation of minerals occurring in the rocks from the Younger Granite complexes includes:

- (a) Studies on the system iron-oxide--silica--water, at low $(O_2)_P$, carried out by Flaschen and Osborn (1957), and mainly concerned with the stability relations of fayalite.
- (b) Studies on the stability relations of riebeckite and riebeckite-arfvedsonite solid solutions, carried out by Ernst (1962).
- (c) Stability relations of the ferruginous biotite, annite, carried out by Eugster and Wones (1962).
- (d) Studies on the phase relationships of biotites on the join phlogopite-annite, carried out by Wones and Eugster (1958).

The results of these experimental studies will be discussed briefly.

(a) Stability relations of fayalite $(Fe^{+2}SiO_4)_1$

Flaschen and Osborn (1957) investigated the system iron-oxide--silica--water, at high total pressure, low $P(O_2)$ and at temperatures between $200^\circ C$ and $925^\circ C$.

Fayalite was found to be stable at temperatures between $250^\circ C$ and $925^\circ C$ at low $P(O_2)$; provided no aqueous phase appeared fayalite was stable down to temperatures of $200^\circ C$. With similarly low $P(O_2)$ and at temperatures above $480^\circ C$, fayalite and quartz co-existed in stable equilibrium. (In all these experimental systems the stability ranges of the minerals being investigated were found to be affected by the formation of other solid phases, e.g. the formation of quartz lowers the stability of ferruginous and other biotites).

In the Younger Granite complexes of Nigeria fayalite is present in syenites, in early intrusions of quartz-pyroxene-fayalite porphyry, and in amphibole-fayalite granites. In the syenites and quartz-pyroxene-

fayalite porphyries the fayalite co-exists with pyroxene of ferroaugite or hedenbergite composition and with amphibole; quartz co-exists with fayalite in all these rocks with the exception of some of the syenites. In the quartz-pyroxene-fayalite porphyry from Liruei (PB.13), the fayalite co-exists with phenocrysts of quartz that have the bipyramidal form that is typical of β -quartz, which is stable over a wide range of temperature above 600°C, dependent on the total pressure. The amphibole in this rock is too calcium-rich to be an arfvedsonite which is known to be stable at low $P(O_2)$ at temperatures near 700°C (see next section). The $Fe^{II}:Fe^{III}$ ratio of this amphibole is high (9.4) and indicates that the $P(O_2)$ was low during the formation of the porphyry. The ilmenite from this rock contains nearly 8% Fe_2O_3 and some excess of divalent oxides, and it is known that ilmenite forms a solid solution series with Fe_2O_3 at temperatures above 600°C (Edwards, 1954) and can also retain excess FeO in solid solution above this temperature. Using the experimental and analytical evidence, it seems probable that the porphyry PB.13 formed under conditions of low $P(O_2)$ and that crystallisation began at a temperature somewhat higher than 700°C. The possible temperature of formation of this rock must remain slightly doubtful as it is rich in fluorine and no data are available as to the possible effects of fluorine on the stability of fayalite. Fayalite, quartz and a calcium-rich arfvedsonite also co-exist in PB.37 from Sha-Kaleri, the amphibole having a $Fe^{II}:Fe^{III}$ ratio of 3.12, and it is likely that this rock formed at a slightly lower temperature (although still near to 700°C) and a much higher $P(O_2)$ than did PB.13.

Other fayalite-bearing rocks such as the Pankshin syenite (PB.48) and amphibole-fayalite granites PB.38 and PB.47 from Sha-Kaleri and Pankshin respectively, have presumably formed at higher temperatures than PB.37 and PB.13, as the former rocks contain fayalite that co-exists with amphibole that is richer in lime and magnesia than the amphibole in either PB.37 or PB.13. The presence of magnetite containing coarse exsolution lamellae of ilmenite in PB.48 supports the suggestion of a high temperature of formation for this rock, as homogeneous titaniferous magnetite is known to form and to start unmixing at high temperatures, although the precise temperature at which unmixing starts is not known

(Vincent et. al. 1957).

To summarise the above discussion; experimental work together with other evidence suggests that fayalite-bearing rocks in the Younger Granite complexes formed at temperatures ranging from somewhere below the upper stability limit of fayalite (920°C), to approximately 700°C . The cessation of formation of fayalite in the Nigerian Granites was probably due to sharp increases in the water and volatile content of the parent magmas, which resulted in high $f(\text{O}_2)$ conditions in which fayalite was not stable.

(b) Stability relations of riebeckite and riebeckite-arfvedsonite solid solutions:

Experimental work on the stability relations of magnesio-riebeckite has been carried out and reported by Ernst (1960), and more recently (1962) Ernst has investigated the stability relations of riebeckite and riebeckite-arfvedsonite solid solutions.

Employing the bulk composition $\text{Na}_2\text{O} \cdot 0.5\text{FeO} \cdot 8\text{SiO}_2$ + excess water, Ernst has synthesised riebeckite and members of a solid solution series extending from an inferred composition of ${}^{\text{O}}\text{Na}_2\text{Fe}''_3\text{Fe}'''_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ to $(\text{Na}_{2.4}\text{Fe}''_{0.6})(\text{Fe}''_{4.3}\text{Fe}'''_{0.7})(\text{Si}_{7.7}\text{Fe}'''_{0.3})\text{O}_{22}(\text{OH})_2$. Physical parameters that governed phase equilibria included fugacity (or partial pressure) of oxygen, $f(\text{O}_2)$, temperature and total pressure, the oxygen fugacity being controlled by copper, iron (+ silica) and nickel oxide buffers. Composition of the amphibole formed varied with $f(\text{O}_2)$. At high $f(\text{O}_2)$, defined by the haemetite-magnetite buffer, the mineral formed was a riebeckite; with declining $f(\text{O}_2)$ and/or increasing T the mineral became more arfvedsonitic with gradual filling of the vacant (A) lattice site, and near the low $f(\text{O}_2)$ limit of magnetite stability the amphibole had an inferred composition close to $(\text{Na}_{2.3}\text{Fe}''_{0.7})(\text{Fe}''_{4.7}\text{Fe}'''_{0.3})\text{Si}_8\text{O}_{22}(\text{OH})_2$, the A-site being full and electronic balance maintained by changes in the ferrous:ferric and Na:Fe'' ratios in the X and Y positions. With the A-site completely filled it was suggested by Ernst that compositional change was effected by replacement of tetrahedral silicon by ferric iron, accompanied by changes in the Na:Fe'' and ferrous:Ferric iron ratios, and at the point where the oxygen fugacity was defined by the magnetite-wüstite, magnetite-iron and wüstite-iron buffers (low $f(\text{O}_2)$), the amphibole had an

inferred composition close to $(\text{Na}_{2.4}\text{Fe}''0.6)(\text{Fe}''4.3\text{Fe}'''0.7)(\text{Si}_{7.7}\text{Fe}'''0.3)-\text{O}_{22}(\text{OH})_2$.

Summarising the main results of the experimental work, and attempting to apply the results to natural systems where Ca replaces the Fe'' in the X-site of the synthetic minerals, it was shown by Ernst that: (a) at low oxidation states and at temperatures just above 700°C , arfvedsonite can co-exist with an iron-enriched salic melt; in natural rocks, judging from the composition of the synthetic mineral, an arfvedsonite formed under the stated conditions would be expected to have a composition near to $[(\text{Na},\text{K})_{2.4}\text{Ca}_{0.6}](\text{Fe}''4.3-4.7\text{Fe}'''0.7-0.3)[\text{Si}_{7.7-8.0}(\text{Al},\text{Fe}''' \text{ etc.})_{0.3-0.0}]\text{O}_{22}(\text{OH},\text{F})_2$; (b) Experimental work showed that riebeckite-arfvedsonite solid solutions are stable at normal magmatic temperatures up to 712°C at 2,000 bars total pressure, and the minerals formed show no sign of exsolution even at moderately low temperatures. As T decreases and $f(\text{O}_2)$ increases in natural rocks, the composition of the riebeckite-arfvedsonite being formed should change, with gradual decrease in the Ca present in the X-site and decrease in alkali present in the A-site, whilst the ratio of $\text{Fe}'':\text{Fe}'''$ should show a considerable decrease; (c) The synthetic work showed that pure riebeckite, with composition approximating to that of the theoretical end-member, is unstable above 512°C at 2,000 bars total pressure. In natural rocks, as has been pointed out by Ernst, such conditions of high $f(\text{O}_2)$, and temperatures below 512°C are most likely to be met with in very late alkali-rich pegmatitic liquids.

In the Nigerian granites the amphiboles nearest in composition to the synthetic arfvedsonite mentioned in (a) above, are A.37 (which is a calcium-rich arfvedsonite), R.20, R.50, R.57 and R.58, which have formulae of the type $[(\text{Na},\text{K})_{2.0-2.5}\text{Ca}_{0.3-0.7}](\text{Fe}'',\text{Fe}''')_{4.8-5.0}(\text{Si}_{7.5}\text{Al}_{0.5})-\text{O}_{22}(\text{OH},\text{F})_2$. All these amphiboles are fluorine-containing and, as Ernst has suggested that the stability of riebeckite-arfvedsonite is increased by the presence of fluorine, it is possible that A.37 formed at a temperature near the upper stability limit of riebeckite-arfvedsonite (712°C), and that the others formed at temperatures slightly below this; partial pressures of oxygen were probably low to moderately high.

In several of the remaining alkali amphiboles from the Younger Granites, R.64, R.65 and R.30, the amount of calcium has decreased slightly relative to alkali, and Si has increased relative to the other tetrahedrally co-ordinated ions. These amphiboles are to be considered as riebeckite-arfvedsonite solid solutions of the type synthesised by Ernst and they presumably formed over a range of temperatures below 700°C. However, at this stage of amphibole formation in the Nigerian Granites there appears to have been a significant difference in the compositional trend in the natural amphiboles, compared with the synthetic minerals. From the synthetic work it would be expected that as the Ca:Ca + alkali ratio decreased, with decreasing Ca, in natural minerals with decreasing T and/or increasing $f(O_2)$, there would also be a slight absolute decrease in the amount of alkali present in the A-sites, but in the natural minerals there is instead an absolute increase in alkali in the A and X-sites, the average alkali content of the amphiboles mentioned above being 2.8 atoms. In the amphiboles from the albite-riebeckite granites, R.3, R.63, R.85, R.92, R.79, there is a further increase in the amount of alkali present in the AX-sites, the average content being 2.9 atoms, and these minerals have generally lower $Fe^{++}:Fe^{+++}$ ratios, and slightly higher Si contents, than the other alkali amphiboles from the Younger Granites. There seems little doubt that the amphiboles in the albite-riebeckite granites formed in alkali-rich residual magmas under conditions of low temperature (possibly near the upper stability limit of "pure" riebeckite) and high $f(O_2)$, and it is necessary to explain the different compositions of the synthetic and natural minerals formed under these conditions. The most probable explanations are (a) in natural alkali-rich residual magmas where conditions are such that riebeckite-arfvedsonite or, possibly, riebeckite can form, a deficiency of alumina in the magma (shown by high normative acmite content of the rock) implies that any excess alkali that is present must either be removed in a late pegmatitic liquid or, if it fails to escape from the consolidating magma, the alkali must go into a ferromagnesian mineral which has vacant lattice sites; in this case, riebeckite: (b) the alkali amphiboles from the Nigerian riebeckite-granites, and those from the albite-riebeckite granites

in particular, show increasing substitution of Li^+ for Fe^{++} , resulting in a considerable electron deficiency in these amphiboles which could have been partly compensated for by additional Na^+ or K^+ entering the vacant lattice sites.

From the results of the work of Ernst on synthetic minerals, and from a consideration of the compositions of the natural alkali amphiboles from the Nigerian granites, it is suggested that: (a) a number of arfvedsonitic amphiboles (with type formulae near to that suggested for arfvedsonite by Miyashiro, 1957) which contain moderate amounts of lime and alumina, were formed in the Nigerian riebeckite granites at temperatures near or a little below 700°C and at low to moderately high $f(\text{O}_2)$; (b) riebeckite-arfvedsonite continued to form in the riebeckite and albite-riebeckite granites over a range of temperatures, and possibly down to the upper stability limit (512°C) of "pure" riebeckite, under conditions of gradually increasing $f(\text{O}_2)$. The continuing entry of alkali into the vacant lattice sites of the natural minerals is contrary to the trend in the synthetic minerals, and is probably due to the alkali-rich, alumina poor, nature of the parent magmas.

(c) Stability relations of the ferruginous biotite, annite:

The stability relations of annite ($\text{KFe}''_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$) have been discussed by Eugster and Wones (1962).

Phase relationships were governed by total pressure (applied as H_2O ; the authors consider their results valid for natural systems only if total pressure is known to have been due to a similar media), temperature and $f(\text{O}_2)$. Changes in total pressure, from 1035 bars to 2070 bars, were found to have little effect on the stability range of of annite, but increases in $f(\text{O}_2)$ increased the values of temperature and pressure at which the mineral was stable; addition of quartz decreased the stability limit of annite from 825°C at 2070 bars pressure, to 705°C at this pressure.

It has been emphasised by Eugster and Wones that application of the stability data for annite to natural minerals is limited by the rarity of annite, and by the fact that substitution of Mg for Fe'' will increase the stability of iron-rich biotites; at 2070 bars pressure

phlogopite decomposes at 1100°C but annite decomposes between 400°C and 825°C at 2070 bars pressure, and between 545°C and 782°C at 1035 bars pressure, depending on the value of $f(\text{O}_2)$. These authors also pointed out that the presence of fluorine greatly decreases the stability of synthetic phlogopite and probably decreases the stability of annite. It is also suggested by Eugster and Wones that the growth of iron-biotite from silicate melts of granite composition, is possible even at low water pressures, as the annite stability curve at the point that gives the $f(\text{O}_2)$ for the magnetite-~~annite~~ biotite buffer, intersects the $\text{P}(\text{H}_2\text{O})$ -T curve for the ternary minimum of the granite system at approximately 600 bars $\text{P}(\text{H}_2\text{O})$; however, the range of $f(\text{O}_2)$ over which annite is stable at the liquidus temperature of the granite system is narrow.

Two of the biotites from the Nigerian granites can be considered in the light of the experimental work; B.1 from the biotite granite of Liruei, and B.29 from the riebeckite-biotite granite of Amo (Table 13), although both are rich in fluorine, they occur in quartz-bearing assemblages, and B.29 co-exists with an iron-rich alkali amphibole, R.30. Experimentally it was determined that at 1035 bars pressure annite and quartz could co-exist between 545°C and 685°C depending on the $f(\text{O}_2)$. As the trend in the Nigerian granites appears to be toward the low pressure, low temperature minimum in the granite system (to be discussed later) it is unlikely that B.29 formed at a higher total pressure than 1035 bars and, therefore, at a temperature higher than 685°C . As the fluorine content of B.29 is high the maximum temperature of formation would presumably have been much lower than 685°C , and a temperature of 600°C or thereabouts is probably a more realistic estimate. The composition of the alkali amphibole from the same rock as B.29, which was discussed in the previous section, also suggests that 600°C was a likely temperature of formation of both these ferromagnesian minerals. The composition of the biotite B.1 from a biotite granite is also that of a ferruginous biotite, but it is richer in fluorine than B.29 and would therefore have been stable at a slightly lower temperature than B.29, probably a little below 600°C . This temperature seems probable in view of the fact that this biotite granite represents the third intrusion in the late volcanic-granitic

cycle of activity in the Liruei complex, and the author has suggested that the earliest (porphyritic) intrusion, PB.13, in Liruei commenced to crystallise at a temperature near 700°C.

Other analysed biotites from the Younger Granites have compositions that lie on the phlogopite-annite join although no magnesium-rich biotite has yet been reported. The stability relations of such biotites are under investigation by Wones and Eugster, and these authors have made a preliminary report of their results (1959).

The stability of biotite on the phlogopite-annite join, co-existing with potash-felspar, magnetite and water vapor, is dependent on $f(O_2)$ although, as in the experimental work on annite, the addition of quartz to the system is believed to lower the upper stability limit of the biotite.

With a haematite-magnetite buffer the stability limits of biotite containing between 60% and 100% annite (this range will probably include the majority of biotites from the Younger Granites) were between 620°C and 540°C; with a nickel-nickel oxide buffer (slightly increasing $f(O_2)$) the stability limits were between 800°C and 640°C; and with a quartz-fayalite-magnetite buffer the stability limits were between 800°C and 700°C. The magnitude of the $f(O_2)$ given by the haemetite-magnetite buffer may be too low to be applicable to the minerals being discussed (Eugster and Wones, 1962, point out that formation of haematite is characteristic of near-surface environments in the earth's crust, where atmospheric oxygen is circulating), and only the stability of biotites formed under $f(O_2)$ conditions given by the other buffers mentioned above will be considered. The most magnesium-rich of the analysed biotites is B.51 (Table 13) containing 6.35% MgO which corresponds to a biotite containing ca. 25% phlogopite, and such a biotite should be stable at temperatures between 740°C and 780°C depending on $f(O_2)$. However, as B.51 comes from a quartz-bearing assemblage, that also contains magnetite and potash-felspar, the stability limits would be lower than this so it is doubtful whether the mineral formed at a temperature higher than 700°C. B.45 is a more iron-rich biotite with only 2% MgO corresponding to a phlogopite content of ca. 5% and the

stability limits of such a biotite would be between 650°C and 730°C, but once again the presence of quartz in the parent rock would reduce these temperatures considerably.

General summary:

It is suggested by the author, on the basis of a comparison of compositions of the ferromagnesian minerals in the Younger Granites with synthetic minerals formed under known conditions of T , P (total) and $P(O_2)$, that the granites and syenites formed over a range of temperatures between ca. 900°C and ca. 515°C, the upper stability limits of fayalite and riebeckite respectively. Crystallisation of the alkali amphiboles in the later intrusives in the complexes was due to conditions of increasing $P(O_2)$ in the alkali-rich residual magmas. Possible temperatures of formation of a number of minerals have been suggested but they are unlikely to be very close to actual temperatures of formation as (1) the total pressures employed in the experimental systems varied between 1000 and 2000 bars, and it is possible that some of the Nigerian granites formed under lower total pressures of water; (2) the compositional trend in alkali-amphiboles from the Younger Granites is different from that in the synthetic minerals, and it is difficult to closely correlate the compositions of the synthetic and natural minerals; (3) the majority of hydrous ferromagnesian minerals from the Younger Granites contain fluorine and the precise effects of fluorine on the stability of these minerals are not known; (4) the natural biotites occur in quartz-bearing assemblages and the effect of quartz on the stability of biotites has only been partially investigated; (5) the synthetic biotites are trioctahedral micas, whereas the natural analysed biotites are obviously solid solutions of di- and trioctahedral micas, and again it is difficult to closely correlate the compositions of natural and synthetic minerals; (6) many of the Younger Granites have been subject to hydrothermal alteration, and a number of the riebeckite granites have been partly albitised, and it is not possible to decide how much alteration, if any, of the ferromagnesian minerals has taken place.

PROBLEMS OF THE EVOLUTION OF THE YOUNGER GRANITES:

There are many problems in connexion with the evolution of the Younger Granite complexes, and as a number of these problems arise directly from a consideration of the distribution of the complexes and of the pattern of igneous activity in individual complexes, a resume of the essential features of the Younger Granites is necessary.

Regional distribution of the complexes:

It has already been pointed out by Jacobson et. al. (1958) that the Younger Granites can be divided into two groups:

1. A northern group, found north of latitude 10° , which the above authors considered to represent an early stage of igneous activity in the Younger Granite Province. (See location Map 1).
2. A southern group, south of latitude 10° , centred around the Jos Plateau.

The complexes in either one of these two groups have many common characteristics and these can be summarised:

1. Northern group of complexes:

Structurally these complexes are of a simple type: early volcanic activity has often been intense with extrusion of rhyolites, mainly of central vent type, that may have been aligned along ring fractures. Limited intrusion of basic rock sometimes occurred during the volcanic cycle and occasionally, as in the Kila-Wurji complex in the north-east, basic rock is the predominant intrusive rock found in the complex. The granitic cycle of activity in these complexes was obviously restricted and the early ring dykes of amphibole-fayalite or amphibole-biotite granite that are abundant in the south, are of less frequent occurrence in the north. In a typical northern complex, Liruei, the granitic cycle of activity consisted of successive intrusions of amphibole-fayalite, biotite, aegirine-riebeckite, and riebeckite granite, and it is rare in the north for any complex to consist of a greater number, or have a greater variety, of granite intrusions than this. Riebeckite granites are slightly more widespread in the northern complexes than are biotite granites.

2. Southern group of complexes:

In the southern complexes the early period of volcanism was less pronounced than in the northern complexes, and rhyolites and other volcanic rocks constitute a small percentage of the total volume of rocks. The early period of granitic activity in these complexes is usually marked by the intrusion of amphibole-fayalite (or quartz-pyroxene-fayalite) granite or porphyry along ring fractures, and these intrusions were followed by further ring or stock-like intrusions of amphibole-biotite, biotite, albite-biotite, riebeckite and albite-riebeckite granite, although not necessarily in that sequence. A single cycle of granitic activity in complexes in the south, may show an intricate pattern of intermittently repeated intrusion of particular rock types, accompanied by intrusions of minor quantities of basic and intermediate rocks. In the Sha-Kaleri complex for example, the Kaleri cycle of activity consists of eighteen separate intrusions that include five different biotite granites, plus syenite and microgabbro. In contrast to the complexes in the north, biotite granites are abundant in the southern complexes and riebeckite granites are comparatively rare.

In many of the southern complexes there has been more than one cycle of granitic activity and the separate cycles of activity may be (a) partly superimposed as in Jos-Bukuru complex where it has proved difficult to interpret the age relations of three cycles of activity, and (b) easily distinguishable as separate cycles of activity due to periodic shifts in the focus of intrusion, as in the Sara-Fier and Pankshin complex where an apparent southward shift in the focus of activity (Turner, 1961) has given rise to five centres of granitic intrusion.

It is also of interest that the late mineralisation associated with the development of ore minerals in the Province, was largely centred on the southern complexes, especially in the Jos Plateau area, e.g. half the tin production in the Province is from alluvial deposits believed to be derived from the biotite granites of the Jos-Bukuru complex. The distribution of the various rock types in the northern and southern groups of complexes is approximately:

- (1) Northern group (including Liruei, Kudaru, Banke, Saiya-Shokobo, Kila-Wurji, Kwandon-Kaya, Ningi, Fagam-Gadama, Tongola, Jere-Sanga):

	<u>Sq. miles</u>	<u>Percent of total</u>
Basic and intermediate rock	110	15
Volcanics	226	30
Amphibole granites	45	6
Riebeckite granites	192	25
Biotite granites	<u>185</u>	24
Total	758	

- (2) Southern group (including Rop, Sara-Fier, Sha-Kaleri, Jos-Bukuru, Vom, Amo-Buji, Rukuba, Afu, Forum):

	<u>Sq. miles</u>	<u>Percent of total</u>
Basic and intermediate rock	11	1
Volcanics	29	3
Riebeckite granites	32	3
Biotite granites	768	77
Amphibole granites	<u>155</u>	16
Total	995	

From the preceding data about the nature of the Younger Granite complexes it is possible to enumerate the various problems of their evolution:

1. The association of basic, intermediate and acid rocks in the Province makes it natural to suggest that fractionation of a basic magma has given rise to the series of intermediate and granitic rocks. Objections to this theory are (a) the absence of intrusions in which there is a gradation from basic through intermediate to acid rock; (b) the paucity of intermediate rocks; (c) the difficulty of deriving the great volume of acid rock that is found in the Province, from an apparently negligible quantity of basic magma; this is a common problem in provinces of basic-acid rock association and has been recently discussed by King (1962). It is, of course, possible that in individual complexes where there are relatively large amounts of basic rock associated with the granites, differentiation of the basic magma has produced the granitic rocks. The problems involved in attempting to derive the large bulk of

granitic rocks from a basic parent also arise if it is suggested that a syenitic magma was the parent of the granites, for syenites are of even more restricted occurrence than basic rocks in the Province. In this connexion, the only example in the Province of a basic to acid series of successive intrusions is in the Sha-Kaleri complex; during the Kaleri granitic cycle the Mbul series of intrusions were apparently injected along a single ring fracture, the sequence of intrusion being microgabbro-syenite-hornblende biotite granite-biotite granite, and there is a gradational contact between the syenite and hornblende-biotite granite (Jacobson et. al. 1958)

2. The difficulty of establishing a genetic relationship between the basic and acid rocks resulted in Black (1958) suggesting that the amphibole-fayalite granites (intrusions of which often initiated the granitic cycles of activity) represent the parent magma of the granitic rocks. One again, the small proportion of amphibole-fayalite granite (about 8% of the total volume) compared with the great quantity of biotite granite (nearly 60% of the total volume) is the chief obstacle to accepting the former rock type as representing the parent magma. Turner (1961) has also mentioned this problem and suggested that the biotite granites are reconstituted rocks; this point will be referred to again later.

In connexion with the problem of the parent magma of the granites it is, of course, necessary to show that the granites have been produced by a homogeneous parent magma, and for this purpose analyses of granites and rhyolites from the complexes have been plotted on the ternary diagram for the system orthoclase-albite-silica (Fig. 21); this system is applicable to the Nigerian granites which contain between 83% and 98% normative (Or + Ab + Qtz). The granites occupy the field occupied by comendites and comenditic-trachytes (Carmichael, 1962) and they trend toward the low temperature, low pressure (500Kgs/cm^2 P_{water}) minimum in the system. There is some scatter in the distribution of the amphibole-fayalite granites, nevertheless they do occupy a reasonably well-defined field of composition. Remembering that such factors as hydrothermal alteration and incorporation of xenoliths have contributed

FIG: 21

Position of rocks from Younger Granite Complexes in the ternary system Qtz-Or-Ab.

M = minima at water pressures of 500 kgs/cm² and 3000 kgs/cm².

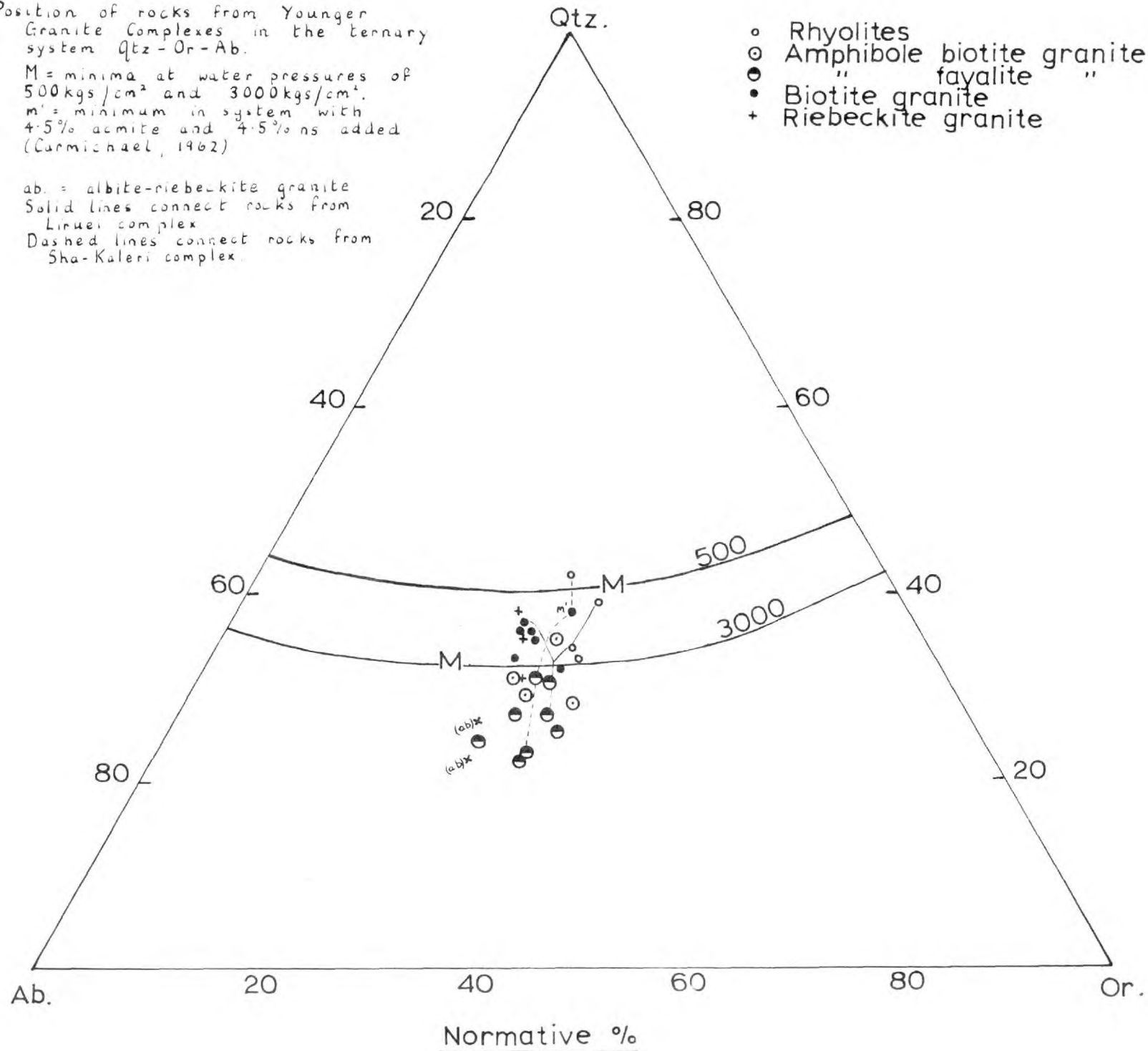
m' = minimum in system with 4.5% acmite and 4.5% ns added (Carmichael, 1962)

ab. = albite-riebeckite granite

Solid lines connect rocks from Liruai complex

Dashed lines connect rocks from Sha-Kaleri complex

- Rhyolites
- ⊙ Amphibole biotite granite
- " fayalite "
- Biotite granite
- + Riebeckite granite



to the compositions of these amphibole-fayalite granites (apart from the possible effects on the analyses of sampling errors), it is perhaps to be expected that the latter rocks will show a degree of scatter when plotted in the ternary system. Tie-lines connect rocks from each of two complexes, Liruei and Sha-Kaleri, and it is evident that rocks from a particular complex may exhibit a certain degree of chemical homogeneity. The biotite and riebeckite granites tend to diverge slightly towards the Ab-Qtz join, and as many of them have been affected by late alkali liquids this is not considered unusual; the anomalous position of the two albite-riebeckite granites in particular confirms that they have been partly albitised.

3. It was mentioned in a previous section that the analyses of the albite-riebeckite granites cannot be matched with the analyses of various volcanic rocks and it was suggested, therefore, that these granites were not of magmatic origin. Similarly, it has not been established that all the other granitic rocks in the complexes have volcanic equivalents and that they originated as liquids. Brown (1962) in discussing the origin of the Skye granophyres, has emphasised that among the more important criteria for deciding whether a granite originated as a liquid are (a) can the granite be chemically equated to a volcanic rock; (b) does the granite show chilled contacts with country rocks; (c) does the granite vein the country rocks.

With regard to (a), a number of analyses of rhyolite are given by Jacobson et. al. (1958) and these do not provide substantial evidence that all the granites have volcanic equivalents, as the analyses are more closely related to the riebeckite granites, and a few of the biotite granites, than to any others:

	<u>Normative composition</u>					
	(a)	(b)	(c)	(d)	(e)	(f)
Qtz	32.3	30.5	38.8	33.8	33.0	24.6
Or	31.9	28.1	27.4	26.7	28.3	30.3
Ab	32.4	29.7	27.7	32.5	33.3	36.2
An	-	-	2.9	-	1.5	0.9
Ac	0.4	6.0	-	2.6	-	1.3
Ns	-	0.3	-	0.3	-	-
Di	0.4	0.8	-	0.1	0.6	2.9
Hy	0.5	2.4	1.4	1.5	1.4	1.5
Mt	0.8	-	1.0	0.5	0.8	1.3
Il	0.3	0.3	0.2	0.2	0.2	0.5
C	-	-	-	-	0.2	-

- (a) is a rhyolite with slight molecular excess of alkali over alumina
(from Buji complex)
- (b) is a comenditic rhyolite from Liruei
- (c) is a late rhyolite from Kaleri complex
- (d) is the average of five riebeckite granites
- (e) is the average of five biotite granites
- (f) is the average of eleven amphibole granites

Descriptions of the rhyolites from various complexes indicate that microcrystalline rhyolites are infrequent; a great many of the rhyolites are spherulitic, the majority of them contain some phenocrysts, many are distinctly porphyritic, and xenocrysts are common in many of the vent-type rhyolites. The analyses mentioned above are of rhyolites containing phenocrysts and, as Bowen (1928) has pointed out, although such porphyritic rocks can closely resemble the parent liquid, chemically, they may show a considerable divergence from the composition of any liquid. However, most rhyolites, pitchstones and pantellerites contain some phenocrysts (obsidians described by Carmichael, 1962, contain up to 20% phenocrysts), and as it is customary to consider that the bulk composition of any of these rocks is close to the composition of the parent liquid, it can perhaps be assumed that the analyses of rhyolites from Nigeria also represent the compositions of parent liquids.

It is significant that in complexes belonging to the southern group, discussed previously, in which the granitic cycles were complicated and in which there are representatives of all the granite types belonging to the Younger Granites, the volcanic cycles of activity were of comparatively minor importance and there are no extensive occurrences of volcanic rocks in these complexes.

With regard to (b) and (c), there is evidence of marginal chilling of the various granite intrusions, both against one another and against volcanic and basement rocks, but it is also common for the biotite and riebeckite granites to develop marginal pegmatities and pegmatitic knots (Jacobson et. al. 1958). In Liruei complex the rhyolite at the riebeckite-aegirine granite-rhyolite contact is said to have been recrystallised. In the Sara-Fier and Pankshin complex, Turner (1961) has described areas of

mixed acid-basic rock where the mixing appears to have taken place whilst both magmas were completely liquid, and these mixed rocks have been veined by later granite intrusions. Jacobson et. al. also give many instances of granite intrusions veining surrounding rocks.

It can therefore be fairly assumed that a number of the granites could have originated as liquids and that others were in a semi-fluid state at time of intrusion; the high volatile and water content of the late intrusions of alkali-rich riebeckite granite no doubt helped to keep these intrusions (which may have been crystal "mushes") in a near fluid state, even at low temperatures.

4. The mechanism by which differentiation was initiated and proceeded in the parent magma of the Nigerian granites is unknown, and any postulated mechanism must explain (a) the production of alumina-rich and alkali-rich fractions to give biotite and riebeckite granite respectively; (b) the repeated production and intrusion of a particular magma type at different stages of a single granitic cycle of activity; (c) the reversals of, and variations in, intrusive sequences in various complexes, e.g. riebeckite granite may be intruded before or after biotite granite. If it is assumed that there is not a connexion between order of formation and order of intrusion of the various magmatic fractions, then it is necessary to find a satisfactory method whereby fractions could be retained in a magma reservoir whilst later formed fractions were being intruded (as has been suggested by Butler et. al. 1962); considering the high volatile and water content of the riebeckite granites generally, it is slightly difficult to accept that they would be retained in a magma chamber whilst less volatile fractions were intruded; (d) the manner in which a new cycle of granitic activity was initiated in any complex.

5. Assuming that the rocks in different complexes and in different granitic cycles were derived by normal magmatic processes from chemically similar parent magmas, it should be possible to establish the chemical relationship between similar rock types in different complexes and between similar rock types in different granitic cycles in the same complex. If it is possible to correlate the compositions of similar rock types in this way (and the compositions of their ferromagnesian minerals), then

it should be possible to establish a time sequence between intrusive phases in different complexes.

6. It is necessary to explain the distribution of rock types and the different patterns of igneous activity in complexes of northern and southern type. It may be that these differences are explicable in terms of significant areal variation in composition of the parent magmas in the northern and southern parts of the Younger Granite Province.

7. The final problem is to explain the origin of the parent magma of the granitic rocks.

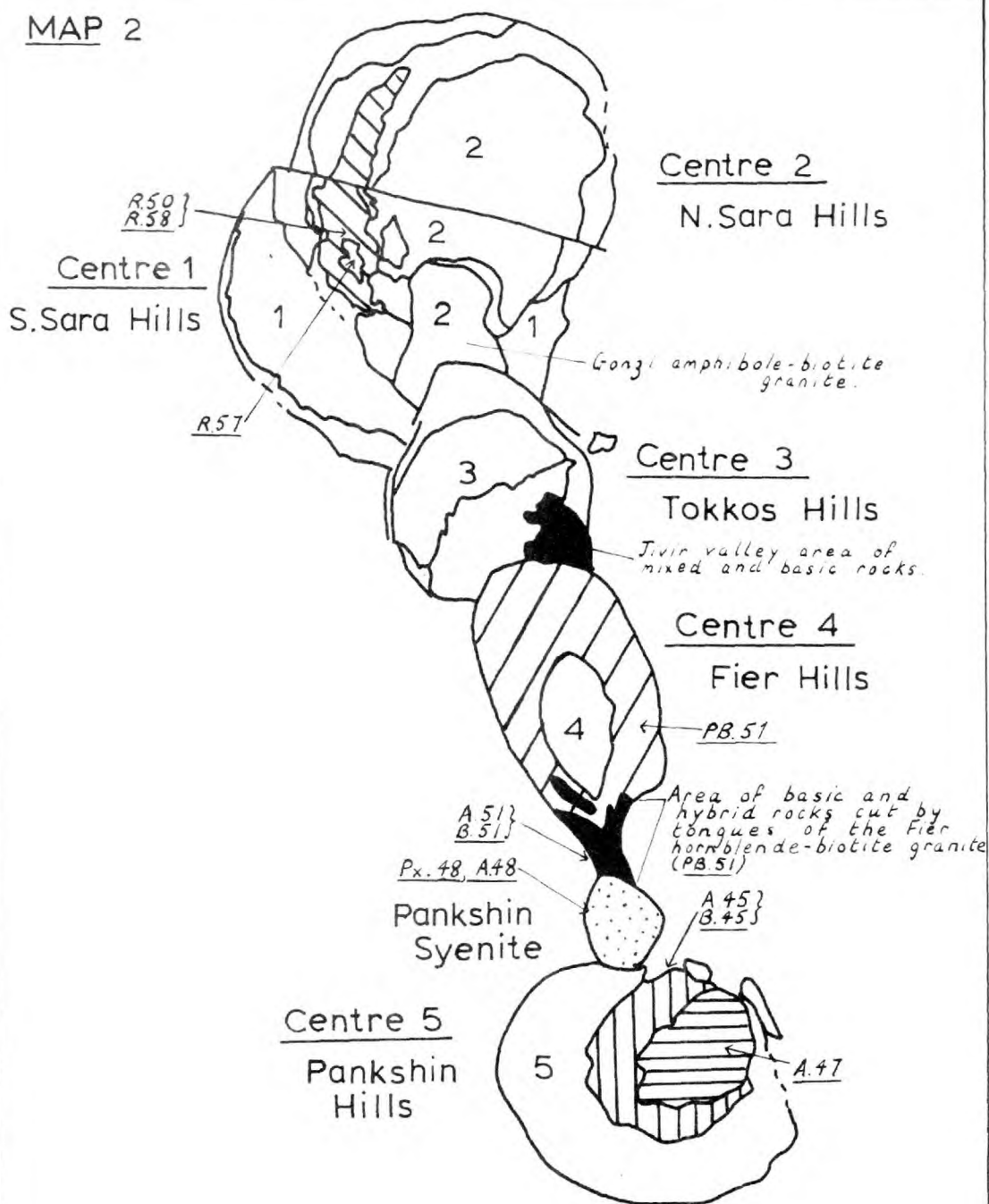
As a consideration of the type of activity found in various complexes might help in answering some of the foregoing problems, a number of individual complexes will be described in the following sections.

The Sara-Fier and Pankshin Complex:

The essential features of this complex have been elucidated by Turner (1961) and are shown in Map 2; there are five distinct centres of igneous activity which are believed by Turner to young to the south, although the presence of the Pankshin Syenite between Centres 4 and 5 make it impossible to determine the relative age of Centre 5. In addition to the five centres of granitic activity there is a small area in the Sara Hills (occurring between rocks of Centres 1 and 2) where volcanic rocks are preserved, and these rocks are thought to be older than the granites of Centres 1 and 2. Two other areas of interest are marked on Map 2; the Jivir valley area where there are fresh and altered basic (dolerites and diorites) and hybrid rocks, and the Fier river area which also contains basic and hybrid rocks that have been partly metasomatised, but the basic rocks in this area are porphyritic and non-porphyritic gabbros. The rocks in the Jivir valley and Fier river areas are considered by Turner to be earlier than the granites of Centres 3 and 4.

Magmatic activity in Centre 1 (the oldest of the Centres to the north of Pankshin) apparently began with intrusion of the Girim granite porphyry, followed by intrusion of the Girim hornblende-biotite granite. For such an early intrusion the hornblende-biotite granite is unusually high in alkali relative to alumina (molecular proportions), and it is also low in iron and magnesia (Table 17, normative analyses reproduced

MAP 2



Sara Fier and Pankshin Complex

5 miles

(After Turner 1961)

TABLE 17

Normative mineralogy of rocks in the Sara-Fier and Pankshin Complex

		Qtz.	Or.	Ab.	Ac.	An.	Wo.	Di.	Hy.	Ol.	Mt.	Il.	Ap.
Centre 3.	Tokkos hornblende- biotite granite	30.73	28.10	38.60	-	0.88	0.10	0.96	-	-	0.63	0.16	0.03
	Kumbul hornblende- biotite granite	27.27	28.30	36.85	-	2.65	-	2.36	0.98	-	1.06	0.38	0.11
	Kadun albite-biotite granite	32.85	27.45	36.85	1.92	-	0.66	0.56	-	-	0.09	0.10	0.05
Centre 2.	Hornblende-pyroxene granite	20.64	32.70	40.94	-	0.15	-	2.80	1.03	-	1.20	0.38	0.11
	Sara amphibole granite	26.33	30.10	38.70	1.16	-	-	1.96	0.44	-	0.96	0.26	0.05
	Gonzi amphibole- biotite granite	29.64	30.75	36.05	-	3.70	-	-	1.74	-	0.67	0.32	0.05
Centre 1.	Girim hornblende- biotite granite	22.59	33.45	34.55	4.88	-	-	3.88	0.21	-	-	0.38	0.05
Centre 4.	Pyroxene-fayalite granite	22.94	27.65	45.05	0.56	-	-	1.80	-	-	1.18	0.24	0.05
	Pankshin syenite	-	30.15	55.60	-	-	-	3.92	1.90	0.48	1.86	0.72	0.37

by permission of Turner), but the petrographic description of this rock, by Turner, suggests that it has been slightly altered and albitised. Granitic activity in this Centre ended with the intrusion of biotite granite but no analysis of the rock is available.

In Centre 2 the granitic cycle began with intrusion of an outer ring dyke of amphibole-pyroxene granite which is richer in alumina, iron and magnesia than the hornblende-biotite granite of Centre 1 (Table 17). The Sara amphibole granite which was intruded after the hornblende-pyroxene granite, is richer than the latter in alkali relative to alumina, and is slightly poorer in lime, magnesia and iron, and appears to be definitely related in composition to the hornblende-pyroxene granite. However, the granite is stated to be of variable mineralogy (Turner) and it is probable that it varies in composition. Intrusion of riebeckite granite followed that of the Sara amphibole granite but the former rock has not been analysed. The riebeckite granite is variable in grain size and there is a distinct small central area of fine-grained material which is not apparently a separate intrusion; the present author has analysed the alkali amphiboles from the coarse (R.50, R.58) and fine-grained (R.57) varieties and there are slight variations in composition of the minerals (Table 9). The next intrusion in this Centre, according to Turner, is the Gonzi amphibole-biotite granite (shown on Map 2) which forms a protuberance to the north of Centre 3. Compositionally (Table 17) this rock is not easily related to the other rocks of Centre 2, being high in normative anorthite, but the rock is rich in xenoliths, some of which appear to have been partly assimilated, and the composition of the rock may be partly due to contamination.

In Centre 3 the earliest intrusion is the Tokkos hornblende-biotite granite, the marginal facies of which is fine grained and which is believed to be made up of a series of arcuate dykes, and it is an analysis of the marginal facies that is given in Table 17. In composition this marginal facies of the hornblende-biotite granite is low in magnesia and, apparently, alumina for it has normative wollastonite, but it is doubtful whether the composition of this marginal material is typical of the hornblende-biotite granite as a whole. The composition of the following intrusion, the Kumbul hornblende-biotite granite, is fairly typical of

hornblende-biotite granites elsewhere, but the composition of the last intrusion in Centre 3, the Kadun albite-biotite granite, is distinctly unusual in that it contains normative acmite and wollastonite (Table 17); there is in fact no other analysed rock from any of the other Younger Granite complexes that contains normative acmite with wollastonite.

The contact between the Kadun albite-biotite granite and the earliest of the two intrusions of Centre 4, the Fier hornblende-biotite granite, is obscured but Turner considers the latter rock to be the younger. The other intrusion in this Centre is a pyroxene-fayalite granite that occupies the central area. An analysis of the pyroxene-fayalite granite shows it to be low in alumina, relative to alkali, and magnesia (Table 17); it contains a small amount of normative acmite and the albite content (45%) is exceptionally high, equalling those of the albite-riebeckite granites from Rop and Liruei complexes, although the rock does not appear to have been albitised. No analysis of the Fier hornblende-biotite granite is available but the author has analysed the amphibole and biotite (A.51 and B.51) from what is thought to be a sample of this rock (the sample comes from the Fier river area where the relationships between acid, mixed and basic rocks are not clear), and they are the most magnesium-rich members of their groups that the author has analysed.

The composition of the Pankshin syenite shows it to be moderately rich in alumina, lime, alkali, magnesia and iron, and Turner concluded that it is related to the granites and not to the hybrid rocks found in the Fier river area. The mineral assemblage in the syenite; ferroaugite (Px.48), fayalite, amphibole (A.48), and titaniferous magnetite with wide exsolution lamellae of ilmenite, point to a fairly high temperature origin for this rock and indicate that it is an early differentiate, possibly related to the granite mentioned previously.

Centre 5 contains three intrusions, the earliest of which was the outer ring of biotite granite and this was followed by apparently almost simultaneous intrusions of the Kula hornblende-biotite granite (PB.45) and the Gate hornblende-fayalite granite (PB.47), the inner contact of these two intrusions being gradational in places. On the basis of the composition of their ferromagnesian minerals (B.45, A.45, A.47) which are relatively

iron-enriched, it seems likely that the rocks of Centre 5 represent fairly late differentiates. Until analyses of the parent rocks are available it is not possible to compare the latter with the rocks of Centres 1 and 2.

Summary:

Early igneous activity in the Sara-Fier and Pankshin complex was located in three different areas and consisted of limited volcanicity in the Sara Hills, and minor intrusion of basic and acid magmas in the Jivir valley and Fier river areas. It is possible that the Pankshin syenite was also emplaced during this early period of activity.

The main granitic cycle started with the intrusion of rocks of Centre 1, followed by those of Centres 2 and 3. The age relations between Centres 3 and 4 and between Centre 5 and the remaining centres, are not clear. The compositional trends in the rocks from various centres are difficult to understand: an early intrusion in Centre 1 is extremely rich in aegirine but the rock has been slightly albitised; the intrusions in Centre 2 show increasing enrichment in alkalis compared with alumina, and this culminated in the formation of riebeckite granite. Following these intrusions were other intrusions of the Gonzi amphibole-biotite granite and an albite-biotite granite which occurs to the north of the former granite. The compositions of the Gonzi amphibole-biotite granite and the granites of Centre 3 are not simply related to those of rocks from Centres 1 and 2, and the former rocks show no systematic variations in composition which can be correlated with differentiation processes in a homogeneous parent magma. In view of the field and chemical evidence it seems probable that processes such as partial assimilation of xenoliths and mixing have contributed considerably to the compositions of the Gonzi amphibole-biotite granite and to the granites of Centre 3. The late intrusion of pyroxene-fayalite granite in Centre 4 is unusually rich in normative albite compared with many of the other granites.

In general the composition of the parent magma of the rocks of the main granitic cycle in the Sara-Fier and Pankshin complex appears to have been moderately enriched in alkali relative to alumina (in terms of molecular proportions) and not very rich in magnesia and, sometimes, lime.

Mixing, contamination and possibly some assimilation of basement rocks, may be the explanation of the slightly erratic variations in composition of some of the granites.

Sha-Kaleri complex:

The Sha-Kaleri complex (Map 3) is in the south of the Younger Granite Province and consists of three partly superimposed cycles of activity, the age relations of which are unknown, although Jacobson et. al. (1958) suggest that the complicated Kaleri cycle initiated intrusive activity. The three cycles of activity were: Monguna, which consists of two intrusions of granite; Tof, which consists of four intrusions of basic, acid and hybrid rocks; and Kaleri, that consists of early volcanics and a large number of crescentically shaped granite intrusions.

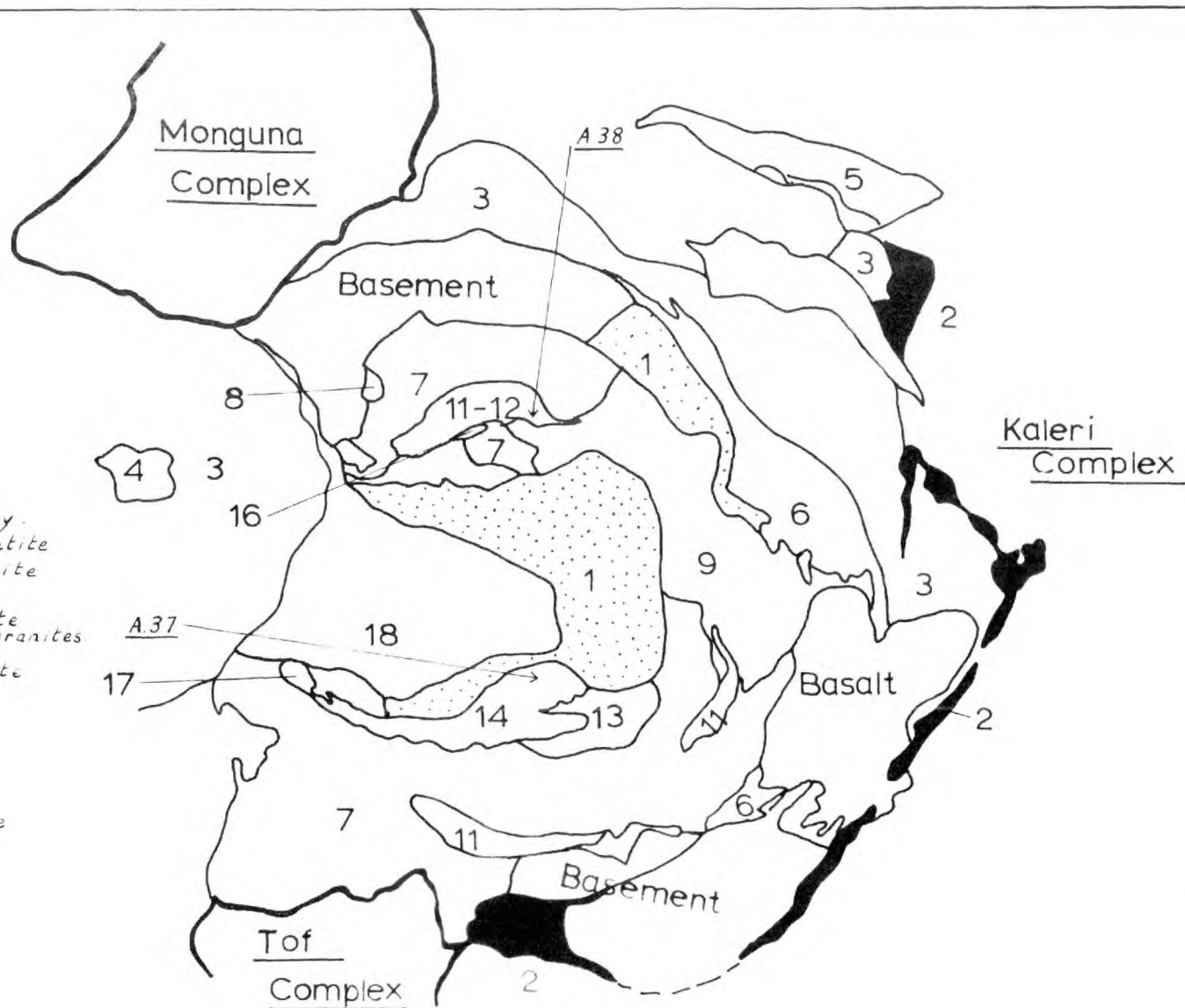
Intrusion in the Kaleri cycle began with the Mbar granite porphyry which contains hornblende, biotite and remnants of fayalite, and this was followed by the Sha-Pitti biotite granite that apparently contains a plagioclase of slightly more basic composition than is usual in the granites ($Ab_{82}An_{18}$). Further intrusions of biotite and fayalite granite followed, including that of the Bargesh biotite granite; an analysis of this rock (Table 18) shows it to be fairly low in calcium and magnesium and it contains normative corundum. The Mbul series of intrusions that apparently occur along a single ring fracture, must represent a slightly different phase of magmatic activity for the sequence of intrusion of the rocks is: microgabbro, quartz-syenite, hornblende-fayalite granite (melanic phase of hornblende-biotite granite), hornblende-biotite granite and biotite microgranite, and the contact between the syenite and the hornblende-fayalite granite (PB.38) is gradational. Analyses of the quartz-syenite and the hornblende-fayalite granite are given in Table 18 and it is obvious that they are closely related; the hornblende-fayalite granite is almost transitional between syenite and the more normal granites in the Younger Granite complexes and in this respect it resembles a pyroxene-hornblende microgranite that is found near Centre 5 in the Sara-Fier complex, which Turner (1961) believes is transitional between the Pankshin syenite and the normal granites. The Mbul quartz-syenite and hornblende-fayalite granite are much richer in lime and magnesia than the Pankshin rocks, but

MAP 3

Monguna
Complex

Kaleri complex

- 18. Biotite granite
- 17. Granite porphyry
- 16. Biotite granite porphyry
- 15. Riebeckite aegirine pegmatite
- 14. Holm arkvedsonite granite
- 13. Biotite granite
- 11-12. Mbul hornblende-biotite granites
- 10. Mbul microgabbro
- 9. Hornblende-biotite granite
- 8. Microgranites
- 7. Biotite granite
- 6. Granite porphyry
- 5. Fayalite granite
- 4. Biotite granite
- 3. Sha Pitti biotite granite
- 2. Mbar granite porphyry
- 1. Rhyolites



4 miles

(After Jacobson et al 1958)

TABLE 18

Normative mineralogy of rocks in the Sha-Kaleri Complex

	Mbul Quartz-syenite	<u>PB.37</u> Hotum arfvedsonite granite	<u>PB.38</u> Mbul hornblende fayalite granite	Bargesh biotite granite
Qtz.	14.31	27.39	18.87	35.5
Or.	21.68	28.36	28.64	30.02
Ab.	34.06	35.27	35.42	30.18
Ac.	-	2.96	-	-
An.	6.45	-	3.58	1.05
Di.	6.00	1.84	7.85	-
Hy.	8.24	1.66	2.97	0.55
Mt.	3.02	1.21	1.34	1.23
Il.	2.74	0.52	1.03	0.16
Ap.	1.27	-	0.41	-
C	-	-	-	0.19

the former rocks both enclose partly assimilated xenoliths of the microgabbro and the resulting contamination must have affected their composition. The amphibole (A.38) from the hornblende-fayalite granite has an iron:magnesia ratio of 78 (Table 16) and is slightly more enriched in magnesia than all the amphiboles analysed by the author, with the exception of A.51. The Hotum arfvedsonite granite (PB.37) is a slightly later intrusion in the complex containing many xenoliths; the analysis is given in Table 18 and it shows the rock to be enriched in alkali and considerably poorer in lime and magnesia than the Mbul intrusions. Iron enrichment is near a maximum in the amphibole of this granite and it is a calcium-rich arfvedsonite (A.37). Granitic activity ended in the Kaleri cycle with intrusion of biotite granite.

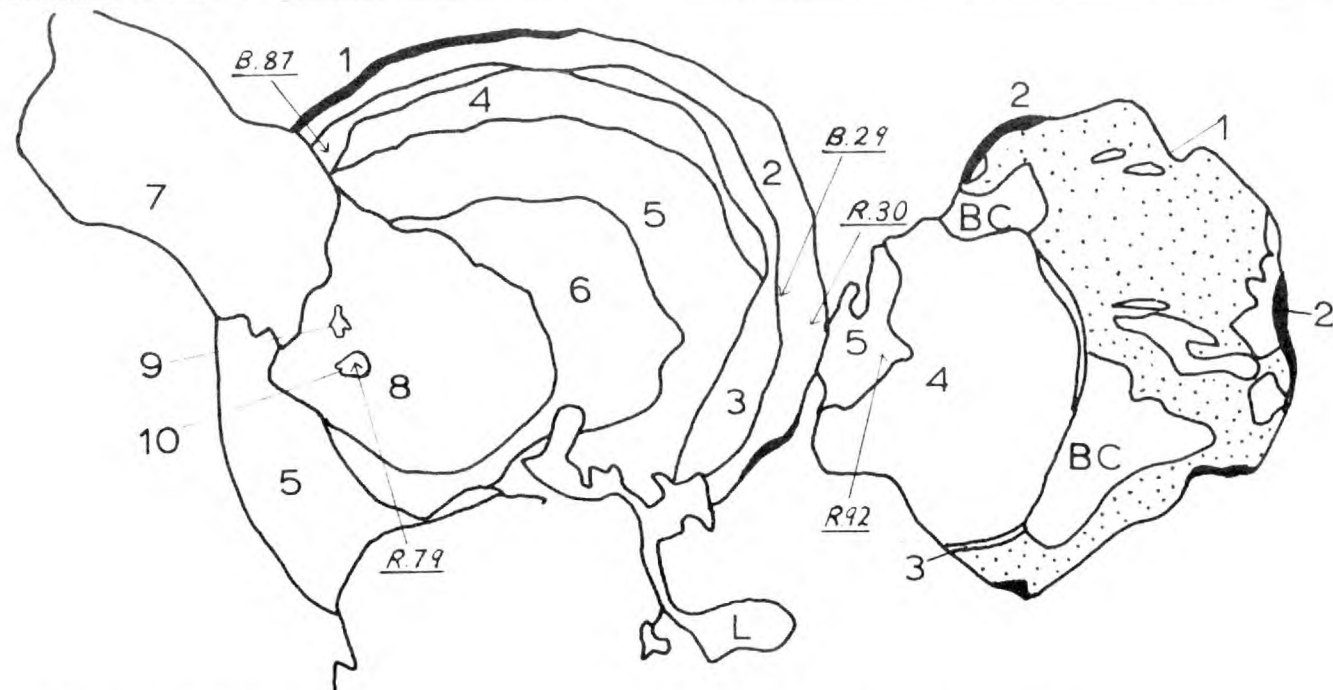
Very little is known of the composition of the rocks intruded in the early phases of granitic activity in the Kaleri cycle (the early phases being considered by the author to include the granites emplaced prior to the Mbul series of intrusions), and it is also uncertain whether the Mbul intrusions are genetically related to the later emplaced granites in the complex. The maximum enrichment in alkalis relative to alumina, in the Kaleri granites, is shown by the Hotum arfvedsonite granite, and it seems probable that the parent magma of the Kaleri granites was relatively more "basic" than the parent magmas in other complexes, for it produced no highly alkaline residual magmas. In view of the very complicated nature of the cycles of activity in the Sha-Kaleri complex, it is obviously desirable to analyse more of the granites intruded prior to the Mbul series in order to determine the degree of variation in, and the relationships between, the early and late intrusions in the complex.

Amo and Buji complexes:

Buji massif lies to the north-west of Jos-Bukuru and consists of Buji complex in the east, composed of volcanic and granitic rocks, and Amo complex in the west, formed solely of granitic rocks (Map 4). There is slight central overlap of the two complexes and in each complex there is evidence of a westerly shift of the centre of magmatic activity during the granitic cycles.

Amo complex:

MAP 4



Amo Complex

- 10. Albite-riebeckite granite
- 9. Hornblende-biotite "
- 4-8. Biotite granites
- 3. Hornblende-biotite granite
- 2. Biotite-riebeckite granite
- 1. Granite porphyry

L. Laterite

Buji Complex

- 5. Albite-riebeckite granite
- 4. Biotite granite
- 3. Aegirine microgranite
- 2. Quartz-fayalite porphyry
- 1. Volcanics

BC. Basement complex

4 miles

Granitic activity began in the complex with intrusion of a narrow ring dyke of granite porphyry that forms the outermost intrusion in the north west, and this was followed by intrusion of riebeckite-biotite granite. The mineralogical variation in this riebeckite-biotite granite indicates that it is a composite body; near the outer contact the granite is rich in alkali amphibole (R.30) and astrophyllite, with very little biotite present, but the percentage of biotite increases toward the inner contact where amphibole and biotite (B.29) are present in approximately equal proportions, and astrophyllite is absent. The analysis of the amphibole (Table 9) shows it is rich in alkali with a Ca:Ca + alkali ratio of 5, and the biotite from the inner contact is near annite in composition, and it contains little alumina (Table 13). Table 19 gives the composition of the parent rock and it is clear that the intrusion is poor in lime and magnesia and has a deficiency of alumina relative to alkalis. The deficiency in alumina is no doubt the cause of the low alumina content of the biotite. It is of interest that the analyses of riebeckite-biotite granites from the Younger Granite Province, given by Jacobson et. al. (1958), reveal that they contain less normative annite than other riebeckite granites and it seems probable that there was a critical ratio of alkali:alumina (molecular ratio) that determined whether or not biotite could form with alkali amphibole in the riebeckite granites; but it is not clear whether the same critical ratio determined whether or not biotite or riebeckite granite would form from the parent magma (as was suggested by Jacobson et. al.). Hornblende-biotite granite formed the next intrusion and although there is no analysis of the rock, the analysis of the biotite (B.87) shows that it is enriched in iron, relative to magnesia, and it has a normal alumina content. Several intrusions of biotite granite followed that of the hornblende-biotite granite, and the analyses of an early one, Teria biotite granite, and a later one, Rough Range biotite granite, are given in Table 19. The Teria biotite granite is richer in alumina, lime, magnesia and iron, than the later Rough Range biotite granite and it is probable that the series of biotite granites intruded during this period show a systematic variation in composition. Near the end of the granitic cycle there was intrusion of a of a very small body of albite-riebeckite granite (PB.79) but the granite

TABLE 19

Normative mineralogy of rocks in the Amo Complex

	<u>PB.29 and PB.30</u> Riebeckite-biotite granite	Teria biotite granite	Rough Range biotite granite
Qtz.	35.25	28.45	33.59
Or.	25.30	29.86	27.86
Ab.	33.90	31.28	27.86
Ac.	1.06	-	-
An.	-	4.03	0.17
Di.	0.94	1.57	0.60
Hy.	1.02	2.86	0.71
Mt.	0.15	0.60	1.11
Il.	0.12	0.60	0.15

has not been analysed.

Buji complex:

The eastern half of Buji complex consists of rocks belonging to the volcanic cycle of activity; early vent and late intrusion rhyolites, and intrusions of porphyry that are similar petrographically to the late rhyolites (and are also similar to the early porphyries in the Liruei complex). An analysis of an early vent rhyolite (given by Jacobson et. al.) indicates that, as in the examples of rhyolites in Liruei complex, the rhyolite from Buji resembles the riebeckite granites in composition, being low in lime and magnesia and containing a slight molecular excess of alkalis over alumina. The granitic cycle in the Buji complex is extremely simple and consists of an early minor intrusion of aegirine microgranite, which was followed by emplacement of an extensive body of biotite granite; the final intrusion was of albite-riebeckite-aegirine granite (PB.92). No analyses of the granitic rocks in this complex are available, but the composition of the aegirine (Ag.92) and amphibole (R.92) from the albite-riebeckite-aegirine granite indicate that they formed from a magma that was considerably enriched in alkali relative to alumina.

Summary:

There are small but interesting differences in the cycles of activity in Buji and Amo complexes. In Buji complex, which is considered to be the earlier of the two complexes (Jacobson et. al.), an early period of volcanicity has resulted in formation of extrusive and intrusive rocks that petrographically and chemically appear to be similar to those in Liruei complex (to be discussed later). The granitic cycle of Buji is also similar to that developed in Liruei, being restricted to a small number of intrusions. In contrast the Amo complex has no volcanic representatives and the granitic cycle consisted predominantly of intrusions of biotite or hornblende-biotite granite. The parent magma of these latter granites was presumably more alumina-rich than the parent magma of the Buji granites, but the high iron content of the biotites (B.29 and B.87) from early intrusions of Amo complex suggest that the parent magma was also depleted in magnesia.

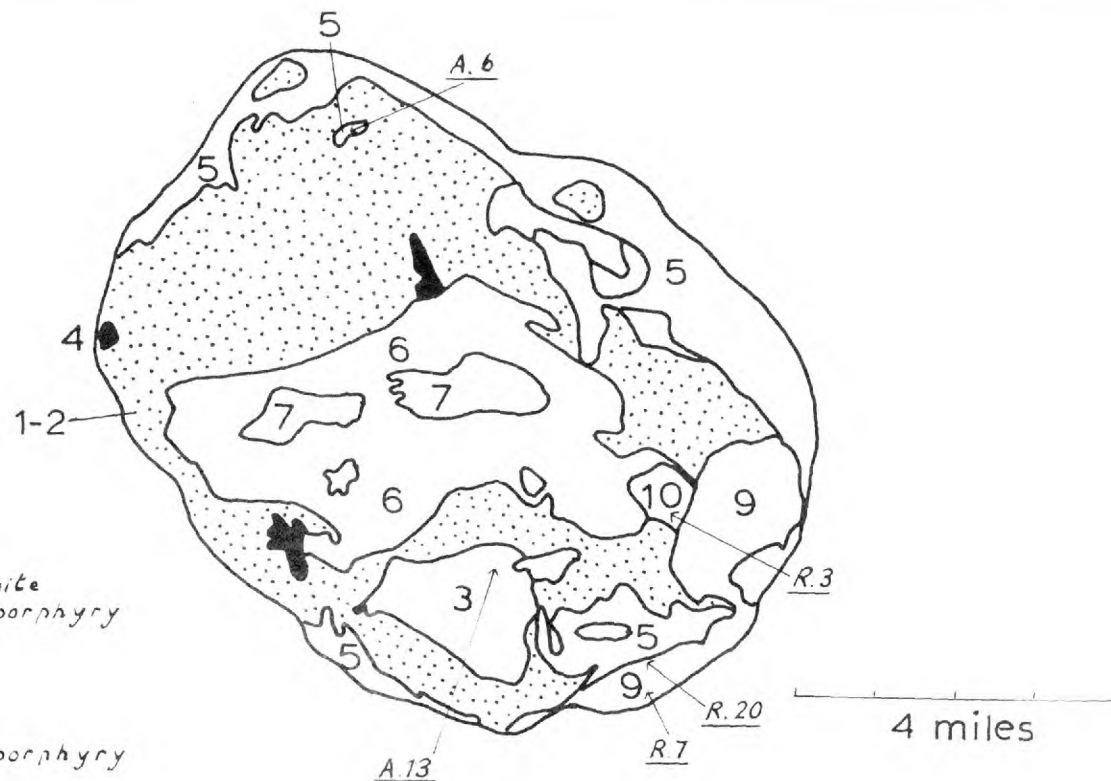
Liruei complex:

In contrast to the complexes previously described, a great part of the Liruei complex is composed of rocks belonging to the early volcanic cycle: rhyolites and tuffs, minor intrusions of basic rock, and a late intrusion of quartz-pyroxene-fayalite porphyry (PB.13).

The rhyolites in this complex are mainly of vent-type and compositionally they resemble the riebeckite granites, having low lime, alumina and magnesia, and the comenditic rhyolite from Liruei is rich in normative acmite, with a little ns. The composition of the quartz-pyroxene-fayalite porphyry (PB.13), which contains the intermediate amphibole A.13, is more alkaline than that of early intrusions of porphyry from many other complexes and it contains normative acmite (Table 20). PB. 6, the amphibole-fayalite porphyry which is the earliest intrusion in the granitic cycle, has a slightly greater molecular excess of alkali over alumina than PB.13 and it is obviously related in composition to the latter porphyry. PB. 6 and the late intrusion of Hotum arfvedsonite granite from Sha-Kaleri are closely alike in composition and they contain somewhat similar amphiboles. The intrusion of biotite granite that followed the porphyry contains less lime, magnesia and iron than the porphyry, but it also has an excess of alumina over alkali and lime and contains normative corundum (Table 20). PB.20, the aegirine-riebeckite granite that followed the biotite granite intrusion, has a composition that closely corresponds to the trend in the porphyries and it shows a further in molecular content of alkali relative to alumina. The last intrusion in the granitic cycle is the Kaffo albite-riebeckite granite which occupies a small area in the east of the complex. The composition of this granite (Table 20) has undoubtedly been completely altered by the albitisation that it has suffered and it contains a high percentage of normative ab, ac and ns; the composition of the rock is reflected in the composition of the alkali-rich amphibole that it contains (R. 3).

The overall trend in the rocks of the Liruei complex is systematic (ignoring the albite-riebeckite granite) and there are decreases in lime, magnesia and iron with successive intrusions, but it is still not clear what mechanism controlled the production of the biotite granite, with its excess of alumina over alkali and lime, in the middle of the cycle. An

MAP 5



Granite cycle

- 10. Albite-riebeckite granite
- 9. Riebeckite-aegirine "
- 8. " microgranite
- 7. Fine-grained biotite granite
- 6. Medium-grained biotite granite
- 5. Amphibole-fayalite granite porphyry

Volcanic cycle

- 4. Basic rocks
- 3. Quartz-pyroxene fayalite porphyry
- 1-2. Rhyolites and tuffs.

Liruei Complex

(After Jacobson et al. 1958)

TABLE 20

Normative mineralogy of rocks in the Liruei Complex

	<u>PB.13</u> Quartz-fayalite hedenbergite porphyry	<u>PB. 6</u> Arfvedsonite fayalite porphyry	Biotite granite	<u>PB.20</u> Aegirine riebeckite granite	<u>PB. 3</u> Daffo albite- riebeckite granite
Qtz.	24.03	25.79	34.91	33.56	22.10
Or.	30.02	30.30	26.19	27.80	24.63
Ab.	34.48	33.27	35.37	27.61	40.19
Ac.	1.94	3.00	-	5.78	5.68
Ns.	-	-	-	-	3.25
Di.	4.47	2.11	-	-	-
Hy.	1.79	1.56	1.40	1.62	2.06
Mt.	1.64	1.81	0.72	0.60	-
Il.	0.65	0.58	-	0.50	-
C.	-	-	1.0	-	-

interesting feature of the rocks and minerals of Liruei complex is their high content of F and Li and, in the case of the albite-riebeckite granite, Zn.

Minerals and rocks from other complexes:

A number of analyses of minerals and rocks from other complexes can be briefly mentioned:

Rop complex: (See location Map 1)

The Rop complex is situated just to the north of Sha-Kaleri complex, and its structure has been determined by a series of polygonal shaped fractures that enclose basement rocks, older granites, and the volcanics and granitic rocks of the Younger Granite cycle.

Early intrusive activity in the complex consisted of emplacement of various porphyries, followed by intrusion of two biotite granites, of which the Gana biotite granite is the later. The Gana biotite granite contains a molecular excess of alumina over alkali, but only moderate amounts of lime, iron and magnesia, and the following intrusion, the Bukka-Bakwai albite-biotite granite, is further depleted in lime, magnesia and iron. The later intrusions, Butra riebeckite granite and Durowa albite-riebeckite granite, show further decreases in lime and considerable increases in molecular content of alkali relative to alumina. The Ruku riebeckite granite porphyry that followed the Durowa albite-riebeckite granite is richer than the latter in alumina relative to alkali and slightly richer in iron (the composition of the Durowa granite has been affected by albitisation), and the late intrusion of Yelwa hornblende-fayalite granite (a rock that is highly variable in texture, mineralogy and content of xenoliths) is relatively enriched in lime, magnesia and iron, and also has a molecular excess of alumina over alkali (Table 21). There are two late intrusions of granite porphyry and biotite granite in this complex but no analyses are available.

The general chemical trend in the rocks from the complex suggest that the Yelwa hornblende-fayalite granite initiated a new short phase of granite intrusion in this complex.

Vom, Kigom Hills, Jos-Bukuru and Shere Hills:

Jos-Bukuru, Vom, Kigom Hills (Forming the north-west tip of

TABLE 21

Normative components of rocks in the Rop Complex

	Gana biotite granite	Bukka Bakwai albite- biotite granite	Butra riebeckite- biotite granite	Durowa albite- riebeckite granite	Ruku riebeckite granite porphyry	Yelwa amphibole- fayalite granite
Qtz	32.36	34.01	32.18	19.81	33.92	24.24
Or	27.52	26.19	26.80	26.03	26.24	30.30
Ab	34.32	36.78	35.74	44.22	35.16	35.27
An	2.39	-	-	-	-	1.33
Ac	-	-	0.83	4.71	1.85	-
Ns	-	-	-	0.27	-	-
Di	0.60	-	-	2.99	0.71	3.30
Hy	1.25	0.91	1.48	-	1.59	3.11
Mt	0.45	0.61	0.90	-	0.23	1.64
Il	0.15	-	0.15	-	0.30	0.58
C	-	0.09	-	-	-	-

Vom, and Shere Hills (in the north-east of Jos-Bukuru), are situated close together in the Jos Plateau area (see location Map 1), and mineralogically the rocks in these various complexes show some similarities.

In the Jos-Bukuru complex early granite porphyries were followed by a hornblende-biotite granite (PB.96); chemically the rock is similar in composition to the Gana biotite granite from Rep, although it is a little richer in magnesia and iron than the latter. The amphibole from the rock (A.96) is very enriched in iron (Table 16) when compared with the amphiboles from hornblende-biotite granites in Sara-Fier complex. A series of biotite granites followed the early hornblende-biotite intrusion and in this respect the granitic cycle in Jos Bukuru resembles that of Amo complex.

The Shere cycle of activity that formed the granites of the Shere Hills in the north-east of Jos-Bukuru (hornblende-fayalite granite PB.71, riebeckite granites PB.64 and PB.65, and albite-riebeckite granite PB.63), is believed to have started mid-way through the Jos-Bukuru cycle (Jacobson et. al. 1958) but there is no definite evidence for this. The amphibole (A.71) from the hornblende-fayalite granite that initiated the Shere cycle is, like A.96, more iron-enriched than the amphibole from hornblende-biotite or hornblende-fayalite granite in either the Kaleri or Sara-Fier complexes. In the riebeckite granites (PB.64 and PB.65) the amphiboles are slightly more enriched in alkali than those from Sara-Fier, but the amphibole from the albite-riebeckite granite (PB.63) is less enriched in alkali than amphiboles that come from other albite-riebeckite granites (Table 16).

An early hornblende-biotite granite (PB.97) from the Ganawuri Hills (Vom) contains a slightly more iron-enriched amphibole (A.97) than PB.96 from Jos-Bukuru, and the albite-riebeckite granite (PB.85) from the Kigom Hills in the north-west corner of Vom, contains a slightly more alkali-enriched amphibole than the albite-riebeckite granite from Shere Hills (Table 16).

General summary:

From the previous descriptions of various complexes it is now possible to make a summary of variations in the pattern of igneous

activity in the Younger Granite Province. It should be remembered that there is still insufficient information about the compositions of rocks and minerals to allow a detailed interpretation of events in particular complexes, and this summary is necessarily generalised and simplified.

The Sha-Kaleri complex (which includes Tof and Monguna complexes) contains minor quantities of volcanic and basic rock, but it has a larger percentage of amphibole-fayalite granite than any other complex in the Province; the parent magma (the nature of which will be discussed later) appears to have been comparatively rich in iron, magnesia, lime and alumina, and biotite and hornblende-biotite granites predominate in the granitic cycle. A moderate degree of enrichment in alkali relative to alumina is shown in the late Hotum arfvedsonite granite, but no alkali-rich residual magmas are represented in the rocks of the Sha-Kaleri complex.

In the Sara-Fier and Pankshin complex, early igneous activity produced basic and granitic rocks, of which the latter may be similar in composition to those of Sha-Kaleri (as it is possible that the relatively magnesia-rich amphibole A.51 and biotite B.51 come from an early granite). The bulk of the granites in the five centres of the complex appear to be more alkali-rich than those of Sha-Kaleri, but the variations in composition in some of the granites of Sara-Fier are slightly erratic. The riebeckite granites in the Sara-Fier complex contain alkali amphiboles with a lower calcium content than does the Hotum arfvedsonite granite from Kaleri.

The parent magma of the early granites in Rop complex was obviously poor in lime, magnesia and alumina, for apart from an early biotite granite, a succession of riebeckite-biotite, albite-riebeckite and riebeckite granites were produced. However, toward the end of the Rop granitic cycle there was intrusion of a lime, magnesia and iron rich amphibole-fayalite porphyry.

In the Jos Plateau area the parent magma that produced the granites of Jos-Bukuru, Vom, and possibly Jarawa, appears to have been enriched in alumina relative to alkali, as hornblende-biotite and biotite granites form the great bulk of these complexes, but it is also probable that the parent magma was low in magnesia for the amphiboles from early intrusions in this

area are iron rich. Minor quantities of alkali-rich residual magma were intruded as riebeckite granites in Shere Hills and Kigom Hills and the alkali amphiboles in these granites show increases in alkali content compared with those from Sara-Fier.

The Buji massif slightly to the north-west of Jos-Bukuru consists of the two complexes, Amo and Buji. In the Buji complex the cycle of volcanic-granitic activity resembles that in Liruei complex further to the north, and the parent magma only produced two major granite intrusions - of biotite and albite-riebeckite granite; the alkali amphibole and aegirine from the latter granite are both extremely rich in alkalis. In Amo complex the granite cycle has been similar to that in Jos-Bukuru with intrusion of a large number of biotite and hornblende-biotite granites. The biotites from granites in the Amo complex are approaching annite in composition, and it is probable that the parent magma was slightly poorer in magnesia than the parent magma of the Jos-Bukuru granites. A negligible quantity of alkali-rich residual pegmatitic liquid in the Amo complex produced the albite-riebeckite granite. The relationship between the rocks of the Amo and Buji complexes is not clear; either the different rock types in the two complexes were formed from different parent magmas, or it must be assumed that the original parent magma split into alumina-rich and alkali-rich fractions, that differentiated to give the two different series of rocks.

Liruei complex, which is the most northerly of those discussed, contains a high proportion of volcanic rocks, a few of which are chemically similar to riebeckite granites. The parent magma was apparently alkali-rich, and iron, lime and magnesia poor, and the granites formed from this parent became increasingly alkaline.

CONCLUSIONS:

It is not possible to come to definite conclusions about, or to offer final answers to, many of the problems of the evolution of the Younger Granite complexes, enumerated previously by the author, but a number of comments about these problems can be made.

1. There is no evidence that the great bulk of the granitic rocks in the Younger Granite Province have been formed by differentiation from a

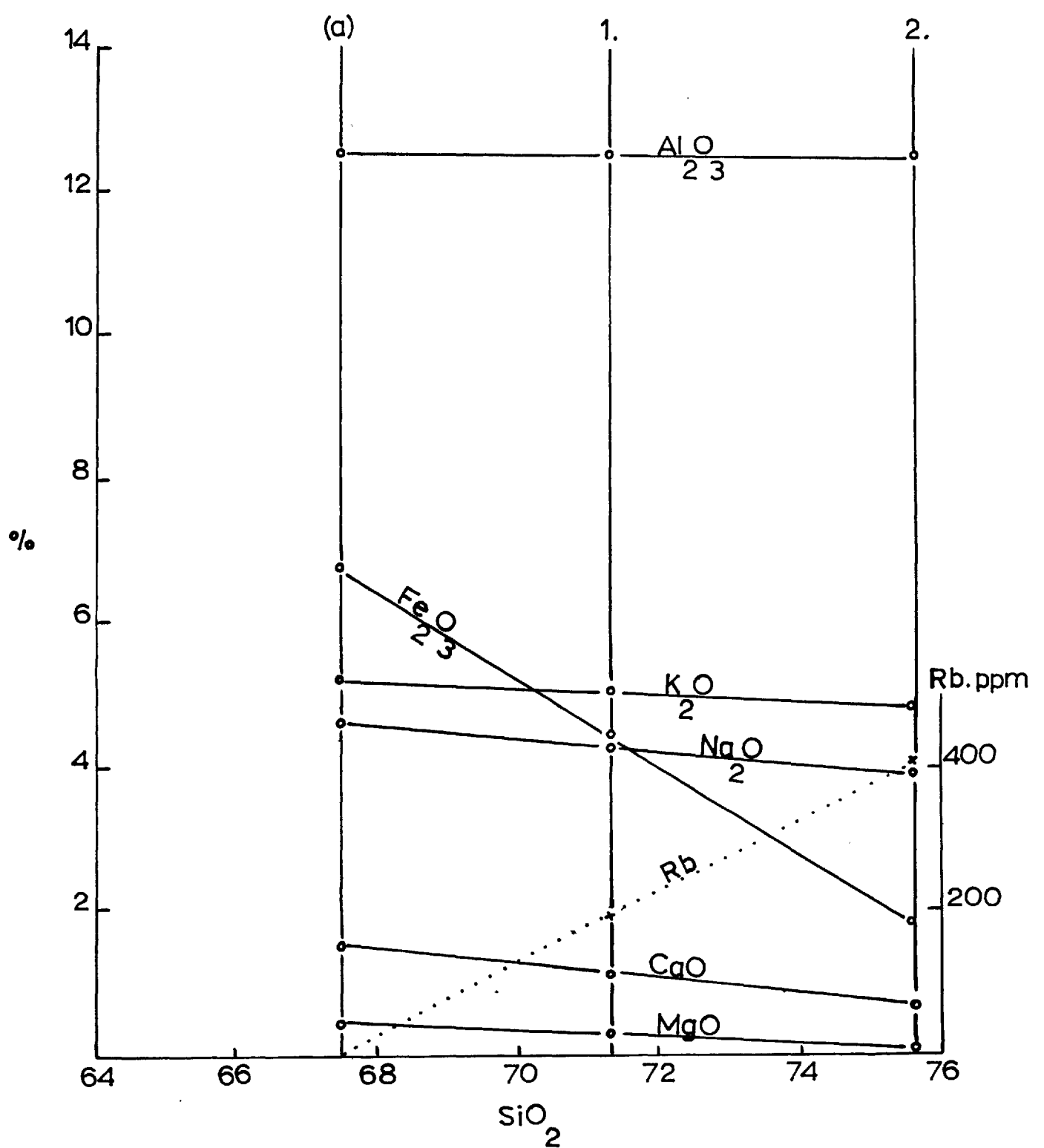
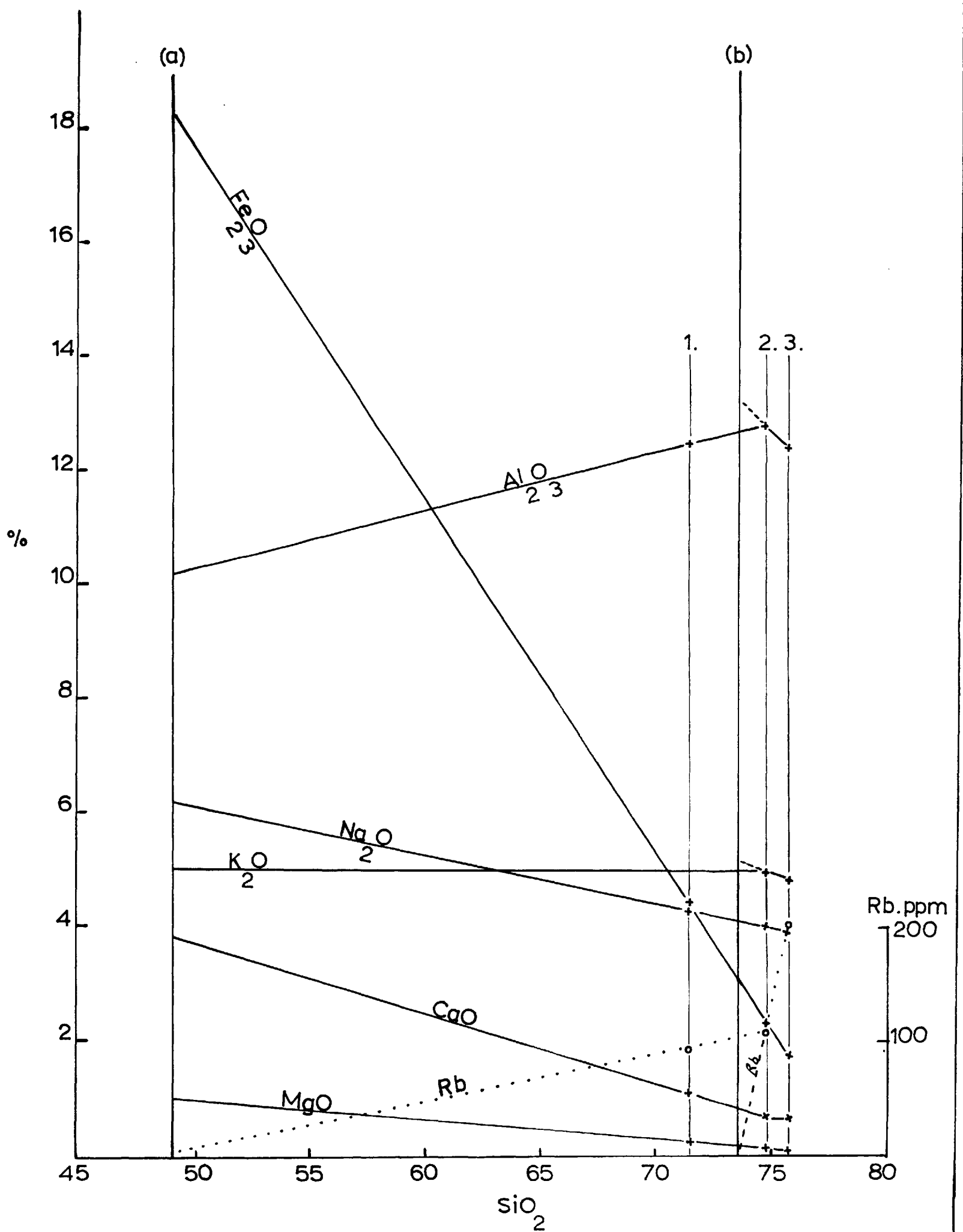
basic magma. The fact that there are small quantities of basic rock in various complexes in the Province is not considered to be significant in this connexion; it is obvious that minor amounts of basic magma were present in magma chambers throughout the Province and this basic magma was intruded sporadically, and sometimes simultaneously with the acid magma.

2. In any series of granitic rocks which have a small range of chemical composition and which lie near the ternary minimum in the system Ab - Or - Quartz, it is obviously difficult to decide which, if any, of the granites represents the parent magma from which other members of the granite series were derived; it is even more difficult to do this when the granites are, as in the Younger Granite complexes, often xenolithic and have been subjected to varying degrees of post-magmatic alteration.

Jacobson et. al. (1958) suggested that the early intrusions of amphibole-fayalite granite and porphyry represent the parent magma of the Nigerian granites and Butler et. al. (1962) have suggested the genetic sequence amphibole-fayalite granite → amphibole-biotite granite → biotite granite, and these authors think there is also evidence for the sequence biotite granite → riebeckite granite. If this genetic sequence does represent the course of differentiation in the Nigerian granites it should be possible to estimate the amount and nature of the material that was subtracted from the liquid at each stage of differentiation in order to obtain the next member of the series. It is necessary therefore to show what material, and how much, could be subtracted from (a) the amphibole-fayalite granite to produce amphibole-biotite granite, and (b) from the amphibole-biotite granite to produce biotite granite.

In Fig. 22(a) the average values of the main components of the three granitic types, amphibole-fayalite, amphibole-biotite and biotite granite, have been plotted against their silica contents, and it will be noted that the variations are not quite linear. In order to decide what material could be subtracted from the amphibole-fayalite granite to give amphibole-biotite granite it is necessary to extrapolate one of the components back to zero content but this is obviously impracticable in the case of the major oxides; for this reason the average Rb values for the three granitic

FIG. 22(a) Shows the major components of (1.) average of 5 amphibole-fayalite granites; (2.) average of 5 amphibole-biotite granites; (3.) average of 5 biotite granites. (a) shows the composition of the material subtracted from the amphibole-fayalite granite to produce amphibole-biotite granite; (b) shows the composition of the material subtracted from amphibole-biotite granite to form biotite granite.



(b) Shows the composition of the material (a) that must be subtracted from amphibole-fayalite granite (1) to give biotite granite (2).

types have also been plotted on Fig. 22(a) as Rb content decreases from biotite granite through amphibole-fayalite granite (Butler et. al. 1962), and this trace component has been extrapolated back to zero.

The Rb content falls to zero at a silica value of 49% and this value represents the silica content of the most basic solid material that could be subtracted from the amphibole-fayalite granite to produce amphibole-biotite granite; by calculation approximately 13.5% of the amphibole-fayalite granite would have to be subtracted in this way. The normative composition of the subtracted material is: orthoclase 23.6%, albite 20.5%, aegirine 14% and magnetite. As all the iron has been calculated as ferric iron the amount of magnetite subtracted cannot be determined and similarly the aegirine content may be too high; nevertheless the subtracted material would consist of alkali feldspar, pyroxene (probably of sodic-ferrosaugite or hedenbergite type) and magnetite. Subtraction of minerals of this type from the amphibole-fayalite parent magma in order to give amphibole-biotite granite was obviously not wholly improbable as these minerals are the same type as those that are present in the amphibole-fayalite granites and porphyries.

It remains to calculate the composition of the material that could be subtracted from the amphibole-biotite granite in order to produce the biotite granites. Fig. 22(a) shows that if the curve for Rb is extrapolated back to zero content through the average values for biotite and amphibole-biotite granites, the most basic material that can be subtracted from the latter granite to give biotite granite has a silica content of 73.5% and the general composition of the subtracted material is between the average compositions of the amphibole-fayalite and amphibole-biotite granites. 45% of the amphibole-biotite granite would have to be subtracted in this way in order to produce biotite granite.

The total areal amount of biotite granite in the Younger Granite complexes is approximately 1400 sq. miles; assuming that the granites extend downwards for at least a mile then the volume of biotite granite is at least 1400 cu. miles. To obtain 1400 cu. miles of biotite granite from amphibole-biotite granite would have required an original volume of 2540 cu. miles of the latter (as 45% of the amphibole-biotite granite had

to be subtracted to produce biotite granite). The production of 2540 cu. miles of amphibole-biotite granite would have necessitated an original volume of 3320 cu. miles of the amphibole-fayalite parent magma (as 13.5% of the latter had to be subtracted to produce amphibole-biotite granite). These are all minimum figures which assume complete fractionation and ignore the fact that the figures would have to be increased considerably if it is shown that riebeckite granites could be derived from the biotite granites.

It is of course possible that the biotite granites were formed directly from the amphibole-fayalite parent magma by subtraction of solid material without the preliminary formation of amphibole-biotite granite (there are very few intrusions of amphibole-biotite granite in the Younger Granite complexes and they are extremely limited in areal extent). Fig. 22(b) shows the composition of the material that would have had to be subtracted from the amphibole-fayalite granite in order to form biotite granite (again using the zero Rb content to indicate the composition of the subtracted material). The composition of the subtracted material: 67.5% silica, 0.5% magnesia, 1.5% lime, 4.6% soda, 5.2% potash and 6.7% total ferric iron, is not unlike some of the Western Upper Layered Series of syenites from the Kungnat Fjeld alkali intrusion (Upton, 1960); mineralogically the subtracted material would consist of quartz, alkali feldspar, magnetite, pyroxene and olivine (the amounts of the latter three minerals would depend on the $Fe^{2+}:Fe^{3+}$ ratio). Approximately 40% of the amphibole-fayalite granite would have to be subtracted to form biotite granite i.e. 2400 cu. miles of parent magma would have fractionated to give ca. 1000 cu. miles of syenitic material and 1400 cu. miles of biotite granite.

It can be concluded therefore that theoretically it is possible to have obtained amphibole-biotite and biotite granites by crystal fractionation of an amphibole-fayalite granite type of parent magma. Two factors make it difficult to accept the postulated means of obtaining the widespread biotite granites and these are (a) the very large original volume of amphibole-fayalite parent magma that would have been required suggest that there should be a larger percentage of amphibole-fayalite granite present in the Younger Granite complexes than there actually is (unless fractionation of

the parent magma was slow and had been almost completed before intrusion of the granites commenced); (b) the very large volume of material that would have had to be subtracted from the parent magma (whether of amphibole-fayalite or amphibole-biotite granite type) in order to produce biotite granite, suggests that there should be some evidence of this material having been subtracted i.e. there should be intrusions of the subtracted material, as it very nearly equalled the biotite granite in volume, but there is no such evidence. In connexion with the problem of the derivation of the biotite granites, it was mentioned previously by the author that Turner (1961) had suggested that the biotite granites were largely reconstituted rocks; that they had been transformed into biotite granites under the action of volatiles (many biotite granites contain fluorite and have replacement textures). Assuming that such a process of extensive alteration would be a post-magmatic one, it seems hardly likely that it would be restricted to a selective and complete transformation of large volumes of certain granite types to biotite granite; such volatile activity would surely have included partial reconstitution of various granites, and a considerable alteration of volcanic, and basement rocks, and of the more alkaline granites. There is little evidence of the latter type of extensive alteration of other rocks (allowing for the fact that many of the granites in the Province have been subjected to a mild degree of hydrothermal alteration), and petrographically the biotite granites themselves give little indication that they originated in this way; their textures are generally similar to those of other granites in the Province and appear to be normal igneous textures. Although it is possible that a small proportion of the biotite granites were formed in this way, until more substantial evidence is presented it must be concluded that the suggestion that a large proportion of the biotite granites originated by reconstitution of other granites by means of the action of volatiles, is unproven.

3. It has already been pointed out by the author that there is no definite proof that all the granites found in the complexes originated as liquids. The few analyses of rhyolite that are available are of rhyolites that compositionally resemble riebeckite granites or, in one example, biotite

granite.

4. The processes of differentiation in the parent magma of the granites whereby (a) a molecular excess of alkali over alumina was produced in the residual magmas which allowed the formation of riebeckite granites containing normative ac or ns; (b) repeated intrusion of biotite and hornblende-biotite granite; and (c) variations in intrusive sequence were possible, still need to be explained.

In connexion with (a), the late intrusions of riebeckite granite from the Younger Granite complexes are characterised by having a molecular excess of alkali over alumina and they contain normative acmite and, sometimes, sodium silicate. The excess of alkali is not due to a particularly high soda content (the riebeckite granites contain an average of 4.5% soda) but to a low alumina content (average 11.2%). If these granites were derived by differentiation from the biotite granites then it is essential to postulate a mechanism by means of which alumina was subtracted from, and alkali accumulated in, the magma from which the riebeckite granites were formed.

Carmichael and MacKenzie (1963) have discussed the way in which a molecular excess of soda could be developed in a trachytic liquid, and so lead to the formation of pantellerites which contain normative sodium silicate. These authors suggest that the "plagioclase effect" (first put forward by Bowen, 1945, in discussing the formation of sodium silicate from mixtures in the plane albite-nepheline-wollastonite) might be a suitable means of producing a molecular excess of soda over alumina. If in a liquid, of the type discussed by Bowen, containing calcium, the calcium goes preferentially into the feldspar (instead of going into a ferromagnesian mineral or accumulating in the liquid) and thereby prevents the formation of pure albite, then the residual liquid will become slightly enriched in soda relative to alumina; this is termed the "plagioclase effect". Carmichael and MacKenzie also suggest that once sodium silicate is present in the liquid the "plagioclase effect" may no longer be operative, and that the calcium present will be incorporated in a calcium-rich pyroxene.

If a molecular excess of soda over the amount of alumina necessary to form albite was produced in the Nigerian riebeckite granites by means

of the "plagioclase effect" then it ought to be possible to show that in biotite granites which do not contain normative anorthite, there is a lime bearing plagioclase present.

The biotite granite from Liruei (Table 20) contains no normative anorthite, but Jacobson et. al. (1958) give the composition of the late plagioclase grains, that rim the perthitic alkali felspar, in this granite as $Ab_{90}An_{10}$, i.e. the calcium has been preferentially taken into the felspar. In the riebeckite-aegirine granite (PB.20) from Liruei, which was intruded after the biotite granite there is a molecular excess of alkali over alumina and the granite contains normative aegirine. The plagioclase in the rock has a composition of $Ab_{95}An_5$ indicating a very low calcium content, but the aegirine (Ag.20) and the alkali amphibole (R.20) from PB.20 contain 1.9% CaO and 2.9% CaO respectively; this may mean that even in magmas where the molecular excess of alkali over alumina was small and the resulting rock does not contain normative sodium silicate, the calcium goes preferentially into a ferromagnesian mineral.

The evidence given by two granites in a Province that contains a very large number of biotite and riebeckite granites is hardly enough to say decisively that the riebeckite granites of Nigeria were produced from the biotite granite type of parent magma by operation of the "plagioclase effect", but the latter could have been the means whereby at least a few of the riebeckite granites were produced.

In regard to (b), consider the sequences in the Jos-Bukuru--Shere Hills, and Rop complexes (from Jacobson et. al. 1958):

- | <u>Jos-Bukuru</u> | <u>Rop complex</u> |
|--|--|
| <u>Late granite cycle</u> | |
| 15. Sabon Gida II biotite-granite | 14. Mongor Granite porphyry |
| 14. Sabon Gida I biotite-granite | 13. Kaskara biotite granite |
| 13. Bukuru biotite granite | 12. Yelwa granite porphyry |
| 12. Shen amphibole-fayalite granite and granite porphyry | 11. Ruku riebeckite-biotite granite porphyry |
| <u>Shere cycle</u> | |
| 11. Albite-riebeckite granite | 10. Durowa albite-riebeckite granite |
| 10. Riebeckite granite | 9. Butra riebeckite granite |
| 9. Amphibole-fayalite granite | 8. Kassa albite-biotite granite |
| <u>Early granite cycle</u> | 7. Bukka Bakwai biotite granite |
| 8. Kuru biotite granite | 6. Gana biotite granite |
| 4 - 7 Biotite granites | 5. Kwop biotite granite |
| 3. Neil's Valley amphibole-biotite granite and porphyry | 4. Granite porphyry |
| 1 and 2. Volcanics | 1, 2, and 3. Rocks of the volcanic cycle |

The actual age of the Shere cycle relative to the granitic cycles in the Jos-Bukuru complex has not been established and it could be regarded as representing a later stage of igneous activity than either of the granite cycles, particularly as the Shere Hills group of intrusions lie outside the area containing rocks of the early and late granitic cycles. However, it is at least clear that there were three distinct phases of activity in the Jos-Bukuru complex, each of which began with intrusion of amphibole-fayalite granite or porphyry. In the Rop complex the granites are generally included in a single cycle of activity, but the author has already suggested that the cycle should be considered as made up of two phases, the first to include the granites up to and including the late riebeckite granite, and the second starting with intrusion of the Yelwa amphibole-fayalite porphyry. In a similar manner it is possible to split the Kaleri cycle of granitic activity into three separate phases, each of which begins with intrusion of fayalite granite or porphyry or, in the case of the late phase, intrusion of a more basic rock. The author suggests that these phases of activity in various cycles of granitic intrusion represent intermittent generation of a parent magma, or intermittent regeneration of activity in the parent magma, that differentiates to give the following granitic intrusions; if this is so then it should be possible to show systematic variation in the composition of the rocks of each phase, and this can be shown at least for the postulated first phase of activity in the Rop complex (Table 21) and, possibly, for the last phase of activity in the Kaleri cycle. Successive intrusions of biotite granite in these phases of activity should show decreasing contents of alumina, relative to alkali (molecular proportions), and the author has previously suggested that this is possibly what happens in the biotite granites of Amo complex. Although intermittent magmatic activity would account for the repetition of various intrusive sequences in different complexes, it will require a considerable amount of analytical work to prove or disprove the suggestion. It will also of course be necessary to suggest a cause of intermittent generation of, or renewal of activity in, the parent magma.

5. Until a more detailed study of certain complexes has been made, it is perhaps premature to suggest a time sequence of formation of any of the complexes in the Younger Granite Province but, tentatively, the author

suggests (a) the Sha-Kaleri complex represents an early period of activity in the Province, perhaps contemporaneous with the formation of the early basic and granitic rocks of Sara-Fier and Penkshin; (b) there are similarities in the sequence of events and in the types of intrusion in the Jos-Bukuru, Vom and Rop complexes, and it is probable that these complexes are closely related in time of formation, and they may have been formed during a period of maximum igneous activity in the Younger Granite Province; (c) complexes in the north such as Liruei are probably representative of a later period of igneous activity. This suggested time sequence is based on variations in composition of amphibole-fayalite granites and porphyries in these complexes, and it assumes that the acmite-rich early porphyries in Liruei complex represent later differentiates than other amphibole-fayalite granites.

(6) The differences in distribution of rock types and the different patterns of igneous activity in complexes of northern and southern type are at least partly explicable in terms of variations in the composition of the parent magma of the granites found in these different types of complex. The relatively short cycles of granitic activity and small numbers of intrusions in the northern complexes could be accounted for if the parent magmas in these complexes were compositionally similar to the early intrusions of amphibole-fayalite granite and porphyry in the Liruei complex; magmas relatively depleted in iron, magnesia and lime and enriched in alkali relative to alumina. Such parent magmas (which would be only slightly more basic than the late intrusion of Motum arfvedsonite granite in Sha-Kaleri complex) would not be capable of producing a large quantity of amphibole granite. The alumina-poor nature of these parent magmas would explain the increased quantity of riebeckite granite in the northern complexes as compared with the small amount of riebeckite granite in the southern complexes. It is also possible, from a consideration of the composition of the rhyolites from Liruei and from the petrographic descriptions of the rhyolites in the northern complexes, that the large proportion of rhyolite in the north is because the high volatile and water content of the comparatively alkaline parent magmas would favour their violent extrusion as lavas along early fractures. Further analyses of rhyolite are obviously necessary in this connexion. Exactly why there should be an areal change in

the composition of the parent magma in the northern and central-southern parts of the Younger Granite Province cannot yet be explained.

7. Perhaps the major problem of the Younger Granite Province, as of other granitic provinces, is what is the origin of the parent granitic magma, assuming that (a) an origin, by differentiation, from a parent basaltic magma is unfeasible, and (b) granitisation has not played a significant part in the formation of the various members of the Younger Granite complexes. Possible origins of the parent granitic magma are (1) from a primary granite magma; (2) from the fusion of basement rocks at depth, followed by differentiation of the resulting magma; (3) from, the fusion and remobilisation of older granitic rocks of the basement complex. The author is not competent to discuss whether or not there is a primary granitic magma underlying the Younger Granite Province of Nigeria, and there is insufficient information available about the compositions of the basement rocks and older granites (that lie concordantly in the basement) found throughout the Younger Granite Province, to permit any consideration of (2) and (3). At the moment therefore no discussion of the origin of the parent magma of the Younger Granites can be entered into.

APPENDIX 1.

Key to Tables in thesis

Nigerian rocks and minerals (Nomenclature as Jacobson et al. 1958):

- PB.48 Pankshin syenite
Px.48 Pyroxene from PB.48
A.48 Amphibole from PB.48
- PB.13 Quartz-fayalite porphyry. Liruei complex.
A.13 Amphibole from PB.13
I.13 Ilmenite from PB.13
- PB.71 Hornblende-fayalite porphyry. Shere Hills.
A.71 Amphibole from PB.71
- PB.47 Fine-grained hornblende-fayalite granite. Pankshin.
A.47 Amphibole from PB.47.
- PB.94 Hornblende-fayalite granite. Jos-Bukuru complex.
- PB.38 Mbul hornblende-fayalite granite. Kaleri complex.
A.38 Amphibole from PB.38
- PB.36 Biotite-hornblende granite. Kaleri complex.
B.36 Green mica from PB.36.
- PB.87 Coarse hornblende-biotite granite. Amo complex.
B.87 Biotite from PB.87.
- PB.45 Hornblende-biotite granite. Pankshin complex.
A.45 Amphibole from PB.45.
B.45 Biotite from PB.45.
- PB.51 Fine-grained hornblende-biotite granite. Pankshin complex.
A.51 Amphibole from PB.51
B.51 Biotite from PB.51.
- PB.24 Hornblende-biotite granite. Sara-Fier complex.
I.24 Ilmenite from PB.24.
- PB.96 Early hornblende-biotite granite. Jos-Bukuru complex.
A.96 Amphibole from PB.96.
- PB.97 Early hornblende-biotite granite. Jos-Bukuru.
A.97 Amphibole from PB.97
I.97 Ilmenite from PB.97.
- PB. 6 Granite porphyry. Liruei complex.
A. 6 Amphibole from PB. 6
I. 6 Ilmenite from PB. 6.
- PB.37 Hotum arfvedsonite granite. Kaleri complex.
A.37 Alkali amphibole from PB.37
- PB. 3 Albite-riebeckite granite. Liruei complex.
R. 3 Alkali amphibole from PB. 3.

- PB. 7 Riebeckite-aegirine granite. Laruei complex.
R. 7 Alkali amphibole from PB. 7.
- PB.20 Aegirine-riebeckite granite. Laruei.
R.20 Alkali amphibole from PB.20.
Ag.20 Aegirine from PB.20.
C.20 Cossyrite from PB.20.
- PB.50 Riebeckite granite. Sara-Fier complex.
R.50 Alkali amphibole from PB.50.
- PB.57 Fine-grained riebeckite granite. Sara-Fier.
R.57 Alkali amphibole from PB.57.
B.57 Mica from PB.57.
- PB.58 Coarse grained riebeckite granite. Sara-Fier.
R.58 Alkali amphibole from PB.58.
- PB.63 Albite-riebeckite granite. Shere Hills.
R.63 Alkali amphibole from PB.63.
- PB.64 Riebeckite-biotite granite. Shere Hills.
R.64 Alkali amphibole from Shere Hills riebeckite-biotite granite.
- PB.65 Riebeckite-biotite granite. Shere Hills.
R.65 Alkali amphibole from PB.65.
- PB.83 Albite-riebeckite granite. Kigom Hills.
- PB.84 " " " " "
PB.85 " " " " "
R.85 Alkali amphibole from PB.85.
- PB.30 Riebeckite granite. Amo complex.
R.30 Alkali amphibole from PB.30.
- PB.29 Biotite-rich facies of PB.30. Amo complex.
B.29 Biotite from PB.29.
- PB.92 Albite-riebeckite granite. Buji complex.
R.92 Alkali amphibole from PB.92.
Ag.92 Aegirine from PB.92.
- PB.79 Albite-riebeckite granite. Amo complex.
R.79 Alkali amphibole from PB.79.
- PB.100 Mama gabbro. Toi complex.
- PB.42 Rayfield-Gona albite-biotite granite.

Other minerals (from Nigeria and elsewhere):

Pyroxene:

- Ag. 3 Aegirine from riebeckite-aegirine granite. Kigom Hills.
(Greenwood, 1951)

Ferroaugite (Carmichael, 1960):

1. From glassy margin of dyke, Thingmuli, East Iceland.

2. From pitchstone margin of intrusion. Skrutther, East Iceland.
3. " " " " " Bondolfur, " "
4. " " " " " dacite lava. Rauthaskritha, East Iceland.

Ilmenite from the Skaergaard intrusion. (Vincent & Phillips, 1954):

1. From hypersthene-olivine gabbro.
2. " middle gabbro.
3. " hortonolite ferrogabbro.
4. " ferrohortonolite ferrogabbro.
5. " fayalite ferrogabbro.

Cossyrite:

- Av. Average of 14 cossyrite analyses (Yagi, 1953).
2A. Cossyrite from porphyritic obsidian. Pantelleria. } Carmichael, 1960.
3A. " " obsidian. Pantelleria.

Biotite:

- B.1 Biotite from biotite-granite. Liruei complex. (Jacobson et. al. 1958)

APPENDIX 2.

Methods used for chemical analysis

Preparation of material for analysis:

After the rock samples had been crushed to mesh sizes between -75 and -176, an initial separation of the ferromagnesian minerals was made by the Frantz Isodynamic Separator, and this was followed by centrifuging of the heavy fraction in methylene iodide to remove any remaining quartz and feldspar. Repeated centrifuging in Clerici solution separated the required mineral from composite grains and other impurities. Nevertheless many of the minerals could not be separated from impurities by these methods, and these minerals had to be hand picked in order to obtain a fraction that was pure enough for analysis. Some difficulty was experienced in separating amphibole from finely intergrown aegirine and from aenigmatite, and in separating amphibole from biotite, but generally the purity of the final fractions is considered to have been greater than 99%.

The quantities of pure material that could be separated varied greatly; for most of the amphiboles the amount was greater than 0.5gm, but for many of the other minerals it was between 0.2gm and 0.5gm, and for the ilmenites it was less than 0.2gm.

Analytical methods:

Colorimetric and gravimetric methods of analysis were used for the determination of SiO_2 , MgO , CaO and total R_2O_3 , and alumina was determined by difference in the usual way. However, when gravimetric methods of analysis are used on iron-rich minerals with low alumina content, the figure obtained for alumina by the difference method is subject to error. Part of the error is due to the fact that the R_2O_3 precipitate contains zirconia, and possibly zinc and lead, but the major part of the error is caused by the presence of platinum that has alloyed with the iron during the double dehydration of silica with HCl . Consequently, for the alkali amphiboles, aegirine, aenigmatite, and ilmenite, the zirconia and alumina were determined separately as follows: 10 to 25mgms of sample were "fritted" with Na_2O_2 , leached in water, and the solution boiled and filtered. The alkaline filtrate was neutralised

and used for the determination of alumina¹ and the residue was dissolved in 3N HCl and used to determine zirconia. Both determinations were made using the colorimetric methods recommended by Sandell (1950, 1959). Colorimetric methods of analysis were used to determine TiO_2 , MnO , and P_2O_5 , and the alkalis were determined by flame photometer. Lithium was determined on the alkali amphiboles by means of the spectrograph² and by flame photometer. For the spectrographic determination a synthetic "alkali amphibole" was made up, of composition similar to that of the Nigerian minerals, and including 1% lithium. This synthetic amphibole was used as a standard with which to compare the natural minerals. Comparison of the photometric and spectrographic figures (Table 9) shows good agreement. Total iron was determined either volumetrically, as FeO , or colorimetrically, as Fe_2O_3 , and FeO was determined by the ammonium vanadate method described by Wilson (1960). For chlorine, fluorine, and water, the methods recommended by Kolthoff and Sandell (1952) were employed. Zinc was determined colorimetrically (after elimination of other interfering trace metals) during trace element analysis using a slightly modified method described by Stanton et. al. (1962). Chromium was also determined colorimetrically on the alkali amphiboles but was always below the limit of sensitivity (100ppm). Where there was sufficient material, the minerals were analysed for the trace elements Cu, Co, Ni, and Pb, using colorimetric methods. Duplicate or triplicate analyses were made on approximately 0.5gm of material for Ni, Pb, Cu and Co, the results being satisfactory for Cu, and Pb, but less so for Ni. Although it was rarely possible to estimate Co because of interference by Zn, where the amount could be determined it was always less than 0.05ppm.

1. A British Chemical standards sample of iron ore, Cert. No. , was used to check precision in the determination of alumina; alumina present was found to be 1. % compared with a given value of 1. %. Determination carried out by Dr. I.S.E. Carmichael, Dept. of Geology, Imperial College.

2. Spectrographic determination carried out by I. Nicholls, Dept. of Applied Geochemistry, Imperial College.

Lack of material and time prevented complete duplication of mineral analyses and results were only checked when the methods being used were known to lack a high degree of precision, or when any particular result was thought to be unusual.

All determinations of H_2O^+ were carried out in duplicate or triplicate, using a sodium tungstate flux, and the results averaged if necessary. Despite this the author considers the method used to be highly unsatisfactory and a more precise and accurate method of estimating H_2O^+ on amphiboles and biotites is necessary.

The spectrographic results for Li were checked by flame photometry but in neither case were duplicate analyses carried out. As both these methods of determining Li are slightly insensitive the degree of agreement between the two sets of results is considered satisfactory.

The precision of the fluorine determination was assessed by estimating the recovery of fluorine from a standard solution of NaF. Recovery from a standard solution was between 95% and 98%.

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TEXT REFERENCES

- Billings, M.P. (1928) ; The chemistry, optics and genesis of the hastingsite group of amphiboles.
Amer. Miner. 13.
- Black, R. (1958) Unpublished thesis. University of Aberdeen.
- Borley, G.D. and Frost, Some observations on igneous ferrohastingsites.
M.T. (1963) Min. Mag. (In press)
- Bowden, P. (1961) Unpublished thesis. University of London.
- Bowen, N.L. (1928) The Evolution of the Igneous Rocks.
Princeton University Press.
- " - (1945) Phase equilibria bearing on the origin and
 differentiation of alkaline rocks.
 Amer. Jour. Sci. 243-A.
- Brown, G.M. (1962) Melting relations of Tertiary granitic rocks
 in Skye and Rhum.
 Min. Mag. (In Press)
- Brown, G. and Norrish,
 K. (1952) Hydrous micas.
 Min. Mag. 218.
- Bragg, W.L. (1937) The Atomic structure of minerals.
 Cornell Univ. Press.
- Buddington, A.F. and Chemistry, Petrology and Mineralogy of
 Leonard (B.F.) 1953 hornblendes in N.W. Adirondacks granitic rocks.
 Amer. Miner. Vol. 38.
- Butler, J.R., Bowden, K/Rb ratios in the evolution of the Younger
 P. and Smith, A.Z.
 (1962) Granites of Northern Nigeria.
 Geochemica acta, Vol. 26.
- Cahen, L. (1961) Review of Geochronological knowledge in Middle
 and North Africa.
 Ann. New York Acad. Sci. Vol. 91. Art. 2.
- Carmichael, I.S.E.
 (1960) Pyroxenes and olivines from some Tertiary acid
 glasses.
 Jour. Petr. Vol. 1.
- " -
 (1962) Pantelleritic liquids and their phenocrysts.
 Min. Mag. 257.

- Carmichael, I.S.E. and McDonald, A.J. (1961) The geochemistry of some natural acid glasses from the North Atlantic Tertiary volcanic province.
Geochemica Acta, Vol. 25
- Carmichael, I.S.E. and MacKenzie, W.S. (1963) Feldspar-liquid equilibrium in pantellerites: An experimental study.
Amer. Jour. Sci. In press.
- Chinner, C.A. (1960) Pelitic gneisses with varying Ferrous/Ferric ratios from Glen Cova, Angus, Scotland.
Jour. Pet. Vol. 1, No. 2.
- Darnley, A.G., Smith, G.H., Chandler, T.R.D. and Dance (1962) The age of fergusonite from the Jos area, Northern Nigeria.
Min. Mag. 256.
- Deer, W.A., Howie, R. and Zussman (1962) Rock forming minerals. Vol. 3.
Longmans.
- DeVore, G.W. 1957. The association of strongly polarising cations with weakly polarising cations as a major influence in element distribution, mineral composition and crystal growth. Journ. Geol. Vol. 65.
- Ernst, W.G. (1962) Stability relations of riebeckite and riebeckite-arfvedsonite solid solutions.
Amer. Jour. Sci. In Press.
- Eskola, P. and Sahlstein, Th.G. (1930) Extrait des Comptes Rendus de la Soc. Geol. de Finlande, No. 3.
- Eugster, H.P. and Wones, D.R. (1962) Stability relations of the Ferruginous biotite, Annite.
Jour. Pet., No. 1., Vol. 3.
- Flaschen, S.S. and Osborn, E.F. (1957) Studies of the system iron oxide-silica-water at low oxygen partial pressures.
Econ. Geol. Vol. 52., No. 8.
- Fleischer, M. (1936) The formula of aenigmatite.
Amer. Jour. Sci. Ser. 5. Vol. 32.
- Foster, M.D. (1960) Interpretation of the composition of the trioctahedral micas.
U.S. Geol. Survey Prof. paper. 354-B.
- Hall, A.J. (1941) Relation between colour and chemical composition in the biotites.
Amer. Min. No. 26.

- Hess, H.H. (1949) Chemical composition and optical properties of common clinopyroxenes. Pt. 1. Amer. Min. Vol. 34.
- Holmes, A. and Cahen, L. (1957) Geochronologie Africaine 1956. Acad. roy. sci. colon. (Brussels). Classe sci. nat. et. med. Vol. 5., No. 1.
- Horne, J.E.T. (1955) An interim report on the age and composition of pyrochlore from Kaffo valley Liruei-n-Kano, N. Nigeria. At. Energy Div. Geol. Surv. Gt. Brit.
- Iwao, S. (1939) Petrology of the alkaline rocks of the Nayosi district, Sakhalin, Japan. Jap. Journ. Geol. Geog., V.16.
- Jacobson, R.R.E., MacLeod, W.N. and Black (R), (1958) Ring complexes in the Younger Granite Province of Northern Nigeria. Mem. Geol. Soc. London, 1.
- King, B.C., and Sutherland, D. (1962) The Nature of basic igneous rocks and their relations with associated acid rocks. Pt. 1. Sci. Prog. Vol. 1. 200.
- Kolthoff, I.M. and Sandell, E.B. (1952) Quantitative Inorganic Analysis. Macmillan. 3rd Edn.
- Miyashiro, A. (1957) The chemistry, optics and genesis of the alkali amphiboles. Jour. Fac. Sci. Tokyo Univ. 11, Sect. 11.
- Muir, I.D. (1951) Clinopyroxenes of the Skaergaard intrusion, Eastern Greenland. Min. Mag. 214.
- Palache, C. and Warren, C.H. (1911) The pegmatites of the riebeckite-aegirite granite of Quincy, Mass., U.S.A. Proc. Amer. Arts & Sci. v. 47, No. 4.
- Phemister, J., Harvey, C.O. and Sabine, P. (1950) Riebeckite-bearing dykes of Shetland. Min. Mag. 211.
- Rees, G. (1960) Unpublished Thesis, Univ. of London.
- Sabine, P.A. (1950) Optical properties and composition of acmitic pyroxenes. Min. Mag. 209.

- Sahama, Th.G. (1956) Optical anomalies in arfvedsonite from Greenland.
Amer. Min. Vol. 41.
- Saldanha, R., Franco, Ilmenita de Vitoria da Conquista, Bahia, Brazil.
R.R. and Santini, P. Bol. Soc. Brasileira de Geol. 1958, 7(1).
(1958)
- Sandell, E.B. (1950 Colorimetric Determination of Trace Metals.
and 1959) Interscience Pub. New York.
- Sauer (1888) Zeitsch d. deutsch geol. gesell. Band XL.
- Schwartz, G.M. (1958) * Alteration of biotite under mesothermal conditions.
Econ. Geol. Vol. LIII.
- Shoda, T. (1957) On probable elliptic vibration of light in
heikolite.
Min. Journ. Japan, Vol. 2.
- Stanton, R.E., McDonald, A.J. and Carmichael, The determination of some trace elements in silicate
I.S.E. (1962) The Analyst. Vol. 87, No. 1031. rocks.
- Stumpfl, E.F. (1961) Contribution to the study of Ore minerals in
some igneous rocks from Assynt.
Min. Mag. 253.
- Sundius, N. (1946) * The classification of the hornblendes and the
solid solution relations in the amphibole
group.
Sverig. Geol. (Årsbok) 40, No. 4.
- Tauson, L.V. and Kravchenko, L.A. Nature and distribution of Pb and Zn in the
(1956) minerals of the Caledonian granitoids of
Susamin batholith of Central Tian-Shan.
Geoch. Publ. Acad. Sci. U.S.S.R. No. 1.
- Tilley, C.E. (1957) * Problems of alkali rock genesis.
Q.J.G.S. Vol. CXIII.
- Tröger, W.E. (1956) Optische Bestimmung der gesteinsbildenden
Minerale.
Stuttgart, Teil. 1.
- Turner, D.C. (1961) Unpublished thesis. University of London.
- Tuttle, O.F. and Bowen, N.L. The origin of granite in the light of experimental
studies.
Geol. Soc. Amer. Mem. 74.
- Upton, B.G.J. (1960) The alkaline igneous complex of Kungnat Fjeld,
S. Greenland.
Medd. om Grønland, Bd. 123.

- Vincent, E.A. and Phillips, R. (1954) Iron-titanium oxide minerals in layered gabbros of the Skaergaard intrusion, East Greenland. *Geochemica Acta*, Vol. 6.
- Vincent, E.A., Wright, J.B., Chevallier, R. and Mathieu, S. (1957) Heating experiments on some natural titaniferous magnetites. *Min. Mag.* Vol. 31.
- Walker, G.F. (1949) Weathering of soil biotites. *Min. Mag.* Vol. 28.
- Wedepohl, K.H. (1953) Untersuchungen zur geochemie der Zinks. *Geochemica Acta*. Vol. 3.
- Whittaker, E.J.W. (1960) The crystal chemistry of the amphiboles. *Acta Cryst.* V.13.
- Wilkinson, J.F.G. (1957) Titanomagnetites from a differentiated teschenite sill. *Min. Mag.* No. 237.
- Wilkinson, J.F.G. (1961) Calciferous amphiboles, oxyhornblende, kaersutite and barkevikite. *Amer. Min.* Vol. 46.
- Wones, D.R. and Eugster, H.P. (1958) Biotites on the join Phlogopite-Annite. *Ann. Rep. Dir. Geophys. Lab.* 1958-59.
- Wright, J.B. (1961) Solid solution relations in some titaniferous iron oxide ores of basic igneous rocks. *Min. Mag.* 253.
- Yagi, K. (1953) Petrochemical studies on the alkalic rocks of the Morotu district, Sakhalin. *Bull. Geol. Soc. Amer.* Vol. 64.